CRITERIA FOR STRUCTURAL TEST

FINAL REPORT
CONTRACT NAS8-29070
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FOREWORD

This report was prepared by the Huntsville Division of The Boeing Company under NASA Contract NAS8-29070. Period of performance was July 11, 1972, through August 11, 1973. The work was administered under the direction of Mr. J. E. Key, NASA/MSFC.

The purpose of the contracted study was to determine technical feasibility of using a single test specimen for performing the three major structural tests; namely, dynamic, fatigue and static tests for aerospace structures.

Boeing personnel who participated in this study include W. H. Armstrong, Program Manager; and D. W. Cornett, J. T. Wrenn and A. R. Farsoun, Principal Investigators.

SUMMARY

In the past structural test programs on space vehicles and airplane structures, two dedicated test vehicles have been fabricated and used; one test article was used for static testing and the other was used for a dynamic or a fatigue test. However, in the interest of economy, the use of one test article for static, fatigue and dynamic testing has been proposed.

This report contains the results of a study to define criteria and techniques of design, analysis and test which permit the use of a single major structural test article for performing dynamic, fatigue, and static testing.

The criteria developed is applicable to both space vehicles and aircraft structures operating in the subsonic or supersonic regime.

The feasibility of such an approach was demonstrated by defining test interactions, compatibilities and incompatibilities between the three different type of tests.

The results of the study indicate that the single test article concept is feasible with a testing sequence of; dynamic test followed by a fatigue and static test.

In developing the criteria to meet the objectives of this study, some of the major questions which were answered follows:

1.   Can a test load level be established to verify ultimate strength which represents a 99.7% probability ($\simeq 3\sigma$) of non-exceedance in the actual "real world" situation; and, at the same time, not significantly alter or destroy the test specimen from a dynamic characteristic and fatigue standpoint; or if dynamic and fatigue tests are performed first, can a meaningful strength test be accomplished?

Answer: A recent study (Reference 18) shows that a static test to near design ultimate load would provide sufficient proof of structural integrity. Also, the probability of encountering design ultimate loads is small. Based on statistical techniques and exceedance data, the studies indicate the following:

SUMMARY (Continued)

1. Analytical methods used to predict design loads should possibly be modified to reflect more realistic probabilities of encounters.

2. Using existing load prediction techniques, static test to fractional levels of design loads can qualify the structure to high reliabilities.

If dynamic and fatigue tests are performed first, a meaningful strength test can only be accomplished if all detrimental cracks are detected, otherwise the test would, at best, verify a fail-safe capability rather than capability to sustain the design ultimate loads. However, because inspection techniques are available to satisfy the stringent inspection requirements that must be imposed on the single test article, a meaningful test can be accomplished without compromising the strength test program.

2. Can a structural dynamic test, which has planned limited amplitudes and cycles not to exceed load or fatigue life, satisfactorily provide structural modes and damping data for POGO, loads, and flight control design characteristics?

Answer: Amplitudes required in dynamic testing are characteristically low and are dependent upon the accuracy resolution of the instrumentation and equipment used. A review of the dynamic test data (Reference 2) for Saturn V indicates that a smaller test amplitude would have given equally accurate results.

3. Can the accumulated damage from the static strength and structural dynamics testing be appropriately added to the specific fatigue testing in order to assess the fatigue life using the same test article?

Answer: Accumulated damage from high static loads will result in an unrealistic fatigue life, if such loads do not occur in service, therefore should not be added to the specific fatigue testing unless their effects are known and are properly accounted for. Dynamic fatigue damage may be added because of their low amplitudes and nonbeneficial effects on fatigue life.

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SUMMARY (Continued)

4. Can the soundness of the "single-test-specimen" approach be veri-
    fied with analysis as supplemented with existing test and flight
    data?

    Answer: The soundness of this approach can be partially verified
    by analysis. This requires that extensive fatigue data including
    the effects of material reactions and environments be available.
    This requires that component testing be performed. Test data
    presently available to the aerospace industry suggests that this
    approach supplemented by a carefully planned development test
    program can be effective in reducing test costs.

5. Can the approach be introduced into the design cycle in order to
    influence selection of materials and component assembly techniques?

    Answer: The single test specimen approach requires that compre-
    hensive and effective research and development tests be performed.
    Successful completion of the static test is dependent on crack
    propagation and fatigue properties of the selected material. There-
    fore selection of the structural material must be based on good
    strength/weight ratio, good fatigue properties, good fabrication
    properties, etc.

Using the information gathered in fulfilling this study, the application
of the single test specimen concept to the Space Shuttle Orbiter shows
that this approach is feasible if cost savings in the Orbiter structural
test program are to be realized.

The most important advantage in using the single test specimen concept
is the cost savings which can be realized. This, however, would be at
the expense of longer testing schedules and possibly more development
tests.

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SECTION 1

INTRODUCTION

1.1   General

In the past structural test programs on manned space vehicles and air-
plane structures, two dedicated test articles have been fabricated and
used; one test article was used for static testing and the other was
used for a dynamic or a fatigue test. However, in the interest of
economy, the use of one test article for static, fatigue and dynamic
testing has been proposed.

It is apparent that technical problems associated with using the same
test article for different types of structural tests include incompatibilities
and interactions between the three types of tests. For example, ultimate
load tests might produce permanent set (damage) in the structural
material thereby reducing the fatigue life of the structure. Similarly,
fatigue tests may initiate fatigue cracks which alter the structure's
ultimate load capability. Further, dynamic testing may "use-up" part
of the structure's fatigue life. Inspite of these incompatibilities, and
the adverse interaction effects on the structural test article caused by
multiple types of structural testing on a single test article, evidence
exists within the industry which strongly indicates that a single test
article may be used.

1.2   Objectives and Scope of Study

The present study (Contract NAS8-29070) was initiated in July 1972 to
study the interaction effects of dynamic, static and fatigue tests with
the objective of defining criteria and techniques of design, analysis and
test which permit the use of a single major structural assembly test
article in verifying structural integrity.

The duration of the study was limited to thirteen (13) months. Hence,
selectivity had to be exercised in the areas that could be adequately
covered in this study period. Accordingly, the study is comprised of
three parts as follows:

(1)   Survey industries wide practices and proven techniques.

(2)   Evaluate incompatibilities and interaction effects of the
        following test requirements: static, fatigue and dynamic
        tests.

1.2   (Continued)

    (3)   Develop structural test approach and associated criteria
        using a single test article which assures structural
        integrity verification.

1.3   Approach to the Problem

Review and evaluation of the current industries practices and techniques
will provide the basis for determining the validity and effectiveness of
existing criteria, methods, and techniques and will aid in determining
more effective methods of structural test programs.

Upon completion of these tasks, those requirements, philosophies,
criteria, methods and techniques characteristic of static, fatigue and
dynamic tests will be evaluated to determine interactions of each test
procedure on the other two test procedures. The test procedures
will also be scrutinized for purposes of defining compatibilities and
incompatibilities between each of the procedures. It is anticipated, for
instance, that in static testing a vehicle such as the space shuttle, the
structure will undergo thermal conditioning prior to actual testing.
That is, the temperature expected during vehicle operation will be
applied to the structure so that material degradations can be properly
accounted for. It is a relatively simple matter, then, to carry the
thermal cycling one step further and apply corresponding cyclic loads.
Thus, in this instance, static and fatigue test requirements can be
made compatible.

Following identification of interactions and compatibilities between the
three required tests, criteria methods and techniques will be developed.

SECTION 2

REVIEW OF MAJOR STRUCTURAL TESTS AND ANALYSIS PROCEDURES

Structural tests are conducted on flight-quality hardware to demonstrate that structural design requirements have been achieved. When commercial airplanes reach production standards, they must be shown to merit a Certificate of Airworthiness. Certification is based partly on calculation, but emphasis is placed on the major acceptance tests. Thus dynamic, static, and fatigue tests are done on full-scale airframes. In these tests, critical design loadings are simulated. The test loadings and durations are designed to give a high level of confidence that, if test specimens perform acceptably, similar items manufactured under similar conditions can survive the expected service environments. In planning the test programs, it is necessary to select appropriate airframes from the manufacturers sequence, and early enough so that the test results would be available in time for the certification.

Structural certification tests are the major tests in a typical hardware development program. The design development tests consist of those tests of materials, structural elements and structural components performed early in the design phase to provide a realistic basis for the design analysis and major structural ground tests. Component tests are conducted after the design development tests, but prior to full-scale static and fatigue tests. These tests are conducted to provide early design information whenever analytical methods may be inadequate to achieve a high degree of confidence in the strength and fatigue properties of the design. With the completion of these tests, static, dynamic, and fatigue tests are performed to demonstrate that structural design requirements have been met.

2.1   Dynamic Testing

The response of any non-rigid body to an excitation is always time varying and will depend upon the body's mass and stiffness distributions. The detailed manner in which the body does respond will determine the nature of the internal loads in the body. The normal chain of events in establishing the dynamic characteristics of the body involve analytical predictions and verification by test. It is a generally accepted practice within the aerospace industry to perfect a single mathematical model through analysis and test verification, and then to modify this basic model to determine responses for various mass distributions and loading conditions.

2.1.1   Dynamic Analysis Procedures

Precisely what is done with dynamic mathe models by various disciplines is not particularly germane to this discussion; the points that are germane are: 1) how are dynamic models generated, and 2) what role does testing play.   The discussion of this paragraph will be restricted to the analysis portion of model generation; subsequent paragraphs will discuss testing aspects.

The present state of the art in generating mathematical structural models in the aerospace industry involves the use of a finite element program, such as NASTRAN. The procedures involve the idealization of a physical structure as an assemblage of finite sized plate and beam elements having definite mathematical properties which may be varied to match the physical structure as closely as possible.   These mathematical properties are manifested in the elemental stiffness matrix K which is used in describing the relationship between nodal forces F, on the element and corresponding nodal displacements, δ .   Thus

$$\{F\} = [K] \ \{\delta\}$$

These elemental stiffness matrices can then be mathematically merged together to form a stiffness matrix for the entire structure being idealized.   If M describes a distribution of discrete masses over the structure, then the classical equation of motion for a single degree of freedom system

$$M\ddot{x} + Kx = F$$

becomes

$$[M] \{\ddot{\delta}\} + [K] \{\delta\} = \{F\}$$

If H is the defined as

$$[H] = [M]^{-1} [K]$$

then it can be shown (Reference 1) that the relationship

$$\omega^2 [I] + [H] = 0$$

can be used to solve for the natural frequencies, ω , and for determining the mode of the structure.   The mode and corresponding frequencies obtained are numerous and theoretically there will exist one mode and

2.1.1   (Continued)

frequency for each degree of freedom in the H or M matrix, or in other words, one mode and frequency for each discrete mass. Practically speaking, however, the higher frequencies in the solution are difficult to describe accurately and are usually of no consequence because of the reduced forcing energy at these frequencies.

2.1.2   Dynamic Test Philosophies

2.1.2.1   Dynamic Test Objectives - The objective of dynamic testing of full scale assemblies is to verify the analytical predictions, that is, to define as many of the natural modes and frequencies of an assembly as is possible, and to define the amount of structural damping.

2.1.2.2   Dynamic Test Requirements - Dynamic tests for the purposes described above are usually referred to as ground vibration test (GVT). The requirements for ground vibration tests are simple, usually specifying only the structural boundary conditions, the number of modes to be defined during testing, instrumentation locations, and excitation points. The boundary conditions specified for the test are usually important only insofar as they match those used in the analytical predictions. The selected boundary condition usually consists of soft support points in an attempt to simulate a free structure; however, rigid boundary conditions are sometimes specified. Instrumentation for a dynamic test consists solely of accelerometers. Excitation points for the test are based on the analytical predictions of modes and are located near maximum amplitude points for the modes of interest. Force and frequency requirements for the excitation forces are also based on the analytical predictions.

2.1.3   Dynamic Test Methods

There is only one general method used in GVT, however, the method varies in detail of application. The method involves the excitation of the structural assembly with vibratory forces. The exciters are usually called "shakers" and the generally accepted method of test requires the use of multiple shakers, usually on the order of 20 for a typical aircraft. A variation of this method uses only one or two shakers. The recorded data in each of these variations is point acceleration versus time. The major difference in the two variations arises in the methods in which the data is evaluated; however, in either case, the end result is a definition of the natural modes and corresponding frequencies.

2.1.3.1　Dynamic Test Article - In GVT of aircraft, the test specimen is nearly always taken directly from the production, that is, it is an actual piece of flight hardware. The specimen is sometimes devoid of cargo or fuel and control surfaces are usually locked in the neutral position. In some cases, however, such as the Saturn V, tank propellants were simulated with water, primarily in the interest of simulating the mass distribution.

Specimen alterations required for GVT are usually very minimal, requiring no modification to internal structure. Alterations consist entirely of those necessary for shaker attachments.

2.1.3.2　Dynamic Test Setup - Of the three types of testing being considered in this study, the dynamic test setup is by far the simplest (See Figure 2-1). In addition to boundary conditions furnished by the simple jigs, the oil from the oleo struts are usually removed and the tires under-inflated in an effort to achieve as soft a support as possible.

2.1.3.3　Load and Environment Simulation - Amplitudes required in dynamic testing are characteristically low and are dependent upon the accuracy resolution of the instrumentation and equipment used during the tests. For example, maximum wing tip amplitudes measured for the Boeing 727 aircraft during GVT was approximately 4 inches; this compares to a wing tip static limit load deflection of approximately 60 inches.

For the first bending mode of the Saturn V, centerline deflection at Station 4190 was calculated to be approximately 4 inches while the static load deflection for a similar mode was calculated to be 12 inches. A review of the dynamic test data (Reference 2) for the Saturn V indicates that a smaller test amplitude would have given equally accurate results. Thus, it is noted that dynamic test deflections, and therefore stresses, are usually small or can be made small compared to limit load stresses. In fact, it is generally assumed that dynamic test stress levels are well below the endurance limit of most materials.

GVT are usually performed at room temperature, with thermal testing being accomplished on separate components as required. This is often necessary because electrical power requirements for simulation of heat loads can be astronomical when considering large heated areas. Also, representation of expected temperature gradients and distribution cannot be adequately achieved.
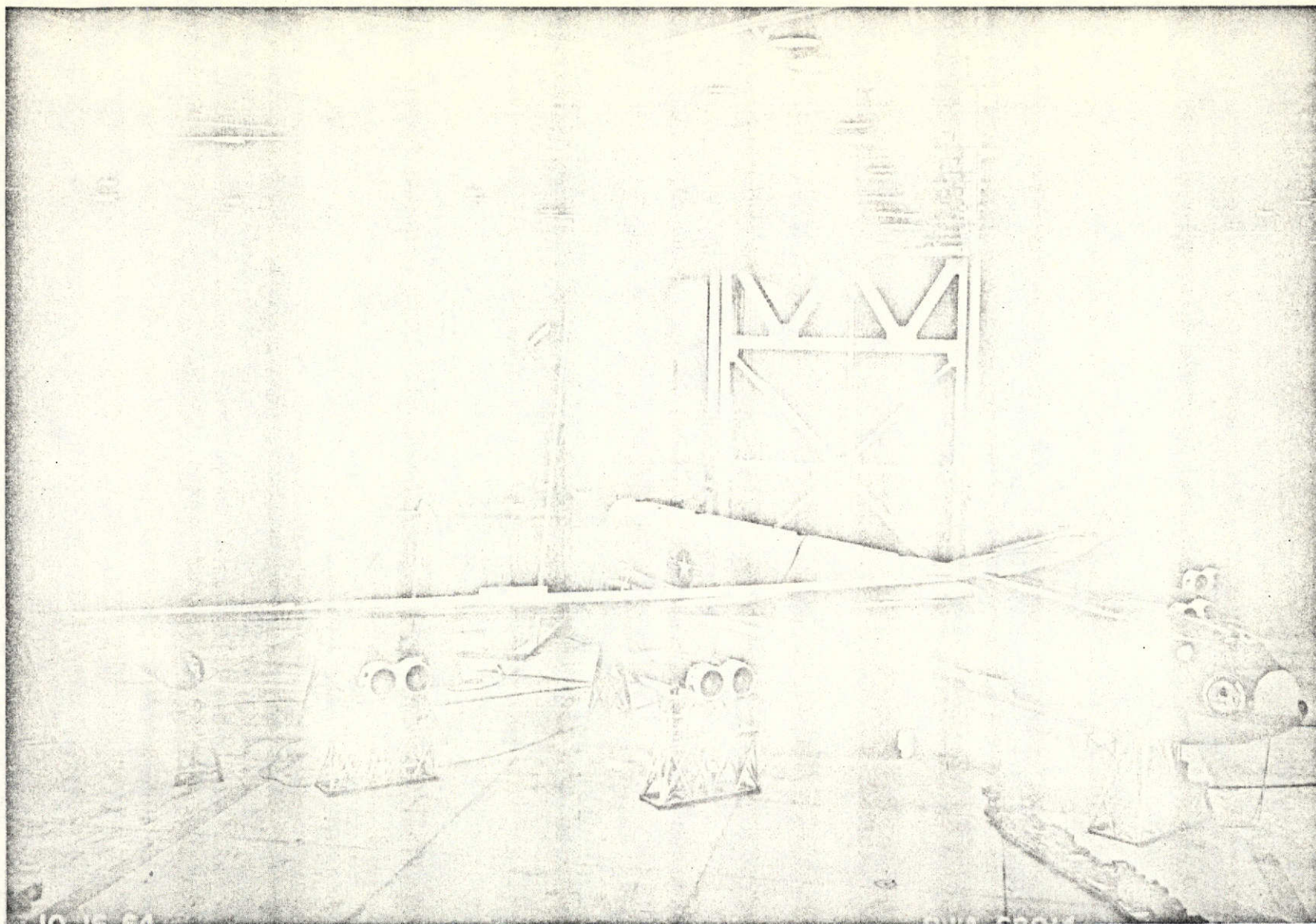
FIGURE 2-1: B-52 DYNAMIC TEST SETUP

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2.1.4 Dynamic Test Results

The raw data from dynamic tests are contained in acceleration-time histories for predetermined points on the structure. These data coupled with visual observations of the tests form the basis for establishing natural modes, frequencies, and structural damping of a given structure.

2.1.4.1 Interpretation of Results

- The data taken during dynamic test are presented in the form of mode shape plots, corresponding frequencies, and structural damping. These data are then compared directly with prior analytical predictions.

2.1.4.2 Application of Results

- Based upon a comparison of dynamic test data and analytical predictions, a review of the mass and stiffness distributions used in the analysis is made. If the mode shapes and frequencies between test and analysis do not match within an acceptable tolerance, refinements are made in these distributions until the match is acceptable. The mathematical simulation resulting from these refinements form the basis for all simulations used in the disciplines of controls, loads prediction, and flutter.

2.2 Static Testing

For any given structure there will exist a number of design environments, composed of loads and temperature, which the analyst has determined to be the most severe of all possible environments. The exact magnitude of the loads and temperature and the probability of encountering such an environment are unimportant from a philosophical point of view, for no matter what the magnitude, the structure will always have to be designed and analyzed for some environment. These design environments then, in the conventional stress analysis, are assumed to occur statically on the structure and the question of the accuracy of the environment does not arise.

The usual static loads analysis generally require many simplifying assumptions regarding load paths, effective structure, etc. Even the sophisticated finite element analyses require a considerable number of simplifications. These assumptions and the amount of detail that must be considered in a complex design require that the structural design be verified through static load testing.

2.2.1 Static Loads Analysis Procedures

For a given design environment, there are four basic steps involved in a static loads analysis:

2.2.1 (Continued)

(1) determination of internal loads and temperature distribution

(2) determination of internal stress distribution

(3) determination of structural allowables

(4) comparison of design stress to allowable stress

The current state-of-the-art in static loads analysis allows for the determination of internal loads, and in some cases the internal stress distribution, through the use of finite element programs. These programs as described in Section 2.1 provide for the mathematical simulation of a continuous structure as an assemblage of finite-sized elements. This simulation can provide a reasonably accurate representation of the elastic behavior of the structure; however, generally speaking, simulation of complex design details such as joints, splices, etc. are not possible. Therefore, the determination of the manner in which a design detail reacts to a given load is determined to an extent by the judgment of the analyst.

Stresses as calculated in a finite element program are usually calculated to be constant over the element. This fact is a consequence of the mathematical models used in the finite element formulation. It is more desirable, therefore, in most cases to use the elemental loads that are computed rather than the elemental stresses. This is especially true if the local simulation at a joint, for example, is intended to represent the stiffness of the structure but not the geometry. Internal loads calculated for plate elements are exceptions to this rule, and it is usually desirable to obtain plate stresses directly from the program.

Having a distribution of internal loads, it is then possible to determine internal stresses using methods contained in any good strength of materials text or structures manual, for example, Reference 3 or 4.

Structural allowables generally fall into the categories of strength allowables and stability allowables. Strength allowables are applicable for structural components subjected to tension, shear, and bending; stability allowables are applicable to thin or slender components subjected to in-plane compressive or shear stresses. A typical and common reference for strength allowables is Reference 5; Reference 3 and 4 contain numerous and typical examples of stability allowables.

2.2.1   (Continued)

The application of these stability allowables usually represents a com-
promise between the actual geometry and boundary conditions of the
structural component and the available allowables data.

The adequacy of a component is ascertained by comparing the applied
stress levels, multiplied by some factor of safety, to the allowable
stress level.   The component is assumed adequate if the modified
applied stress is less than the allowable stress.   The factor of safety
used to modify the applied stress is a variable depending upon its
application; it is intended to account for uncertainties in the design
environment, manufacturing defects, inaccuracies in the stress analysis,
and deficiencies in design details. *

2.2.2   Static Test Philosophies

   2.2.2.1   Static Test Objectives - Static tests are performed
with three objectives in mind:

   (1)   verify the analytical results

   (2)   isolate design deficiencies

   (3)   establish the growth potential

   (4)   clear the vehicle for operation

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* The factors of safety approach has long been suspected of providing
designs that were overconservative, since the approach is one based
strictly on experience and degree of success.   A more plausible
approach has been proposed which would take into account the statis-
tical variations of all parameters affecting a design.   Such an approach
would guarantee a minimum probability of success of a given design,
resulting in factors of safety that would be controlled by the amount of
variance that could be tolerated in the design parameters.   For
example, if loose control were exercised over these parameters,
large factors of safety would be required; whereas, for tight controls,
low factors of safety could be used.

2.2.2.1   (Continued)

The verification is usually established by comparing stresses from tests to those obtained in finite element analyses or equivalent methods. Load magnitudes on the order of 40 percent of limit load are usually sufficient to verify the elastic analysis.

Design deficiencies in a complex structure are common unless the structure is grossly overdesigned. Many of these deficiencies are determined directly from test in the form of premature failures while others are established in the comparison of test and analytical results. To establish these deficiencies, a minimum test load equal to the design limit load is required, however, based on historical practice, the test load is equivalent to ultimate design loads.

To establish the full potential of the structure, or alternately its growth potential, a test load beyond the design ultimate load is required. Obviously, the possibility of a catastrophic failure at such a load is very high (See Figure 2-2).

2.2.2.2   Static Test Requirements - Static test requirements generally consist of the following items:

(1) Definition of the test specimen

(2) Test setup requirements

(3) Load and environment simulation

(4) Instrumentation

Definition of the test specimen is usually a simple reference to an assembly or component drawing number. Test setup requirements specify the boundary conditions to be used in the test, specimen orientation, test fixture stiffness, and specimen safety requirements. * Loading conditions

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*For example, in testing wings for large aircraft, each loading system includes a long ductile linkage. If a loading system (consisting typically of a hydraulic cylinder, a load cell, and link) is suddenly removed from the specimen due to a premature specimen or load system failure, the wing will behave elastically and develop an abnormal deflected shape at the point where the load was removed, thus increasing the local bending stresses and giving rise to overload on adjacent systems and other failures. However, the overloads on adjacent systems will grossly deform the ductile linkages providing for smooth elastic deflections, reducing the likelihood of specimen damage.

FIGURE 2-2:   SPECIMEN DAMAGE RESULTING FROM STATIC TESTS

NASA CONTRACT NAS8-26918

SATURN V/S-II-4 CONFIG. TESTS
BOEING MEMO: 5-9314-H-4, 2/23/70

LEGEND:

● FAILURE*

○ NO FAILURE
   TEST STOPPED

FAILURE TESTS OF 20 DESIGNS

NUMBER OF TESTS

PERCENT LIMIT LOAD

ULT.
DESIGN
LOAD
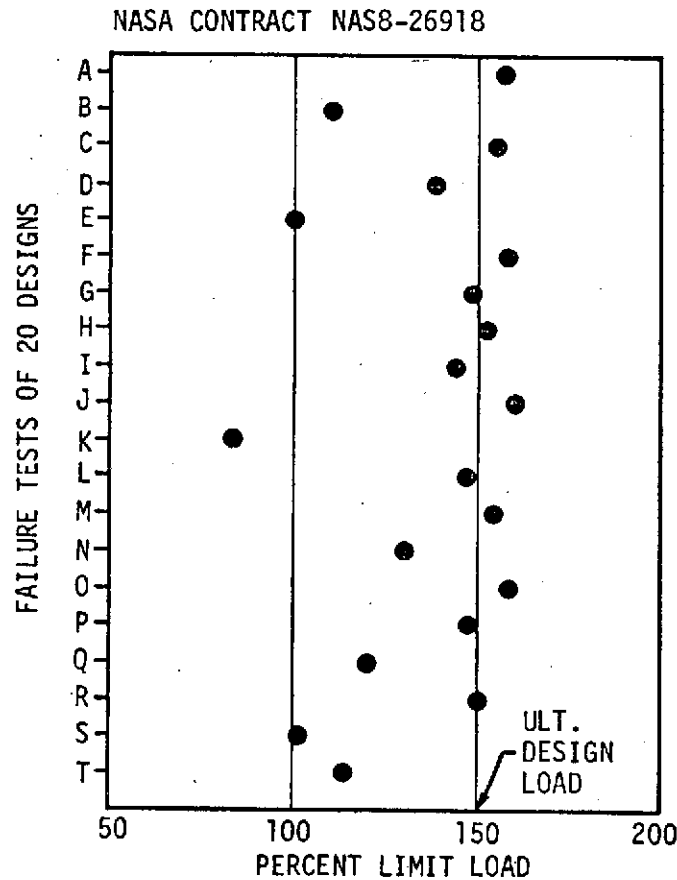
● FAILURES ≤ LIMIT: 1 IN 10 (10%)

● FAILURES < ULTIMATE > LIMIT: 5 IN 10 (50%)
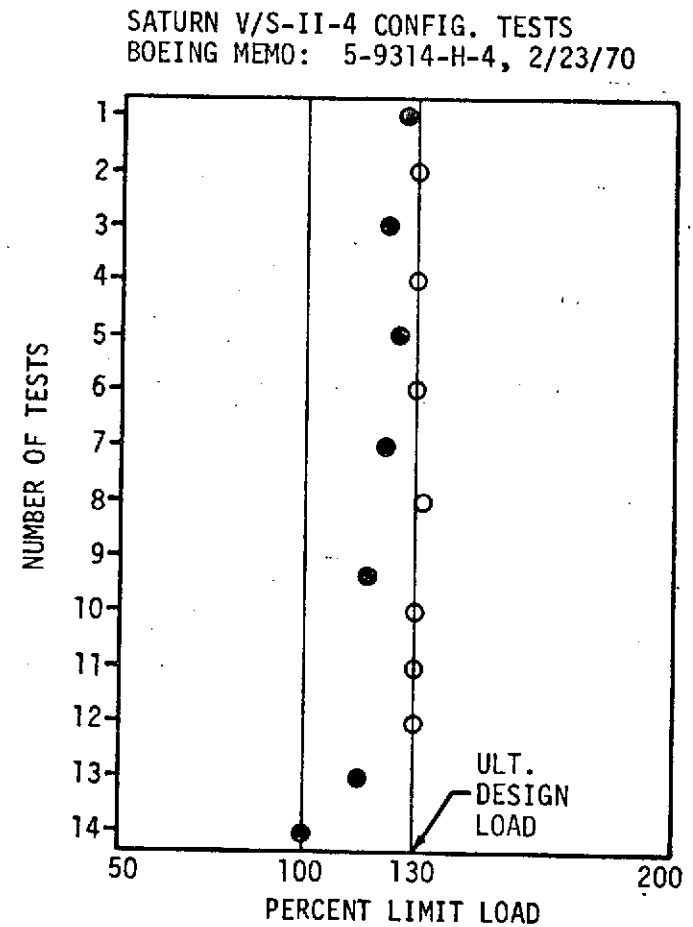
● FAILURES ≤ LIMIT: 1 IN 10   (10%)

● FAILURES < ULTIMATE > LIMIT: 4 IN 10
   (40%)

*FAILURE IS DEFINED AS THE INABILITY OF THE STRUCTURE TO SUSTAIN FURTHER LOADING.

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2.2.2.2   (Continued)

specified for static testing include load and temperature distributions, rates or increments of loads and temperature application, sequence of load conditions, and maximum amplitude of applied load. Instrumentation for static testing consist of strain gages, deflection indicators, and thermocouples.

2.2.3   Static Test Methods

2.2.3.1   Static Test Article - Test articles used in the static tests are structurally very nearly identical to flight vehicles. They differ by whatever is required to safely apply large concentrated loads. For example, modification to the Boeing 747 center wing spar was performed where necessary to insure that high concentrated loads were applied to the spar shear web rather than the angle forming the spar cap. Other significant modifications to the structure are holes; these modifications are expedient for the application of load, but if required, could probably be avoided.

2.2.3.2   Static Test Setup - Static tests are usually performed in an area with specially prepared floors containing many tie-down points. These points are used to secure fixtures supporting the specimen and loading system. The floor provides the link between the applied load and reaction points necessary for a self-contained loading system. A specific static test setup can probably be considered unique since it cannot be used for any other static tests. It consists of sufficient fixtures to accommodate all loading fixtures and to restrain the specimen. Examples of test setup is shown in Figure 2-3; however, it is noted that the relevance of the test setup is not what its detailed configuration is but whether or not it can accommodate other types of testing. This topic will be discussed in Section 4.0.

2.2.3.3   Static Load Application System - Loads and temperatures applied to a test specimen represent a compromise between what is theoretically correct (based on best estimates) and what is practical to achieve. It is generally necessary, for instance, to apply a distributed load as a set of concentrated loads, with the idea that a sufficient number of these concentrated loads will closely represent the distributed loads -- or at least the overall effect of these loads. These concentrated loads are typically applied through tension or compression pads or through loading blocks. The specific nature of these load application devices will depend on the designs of the structure and the

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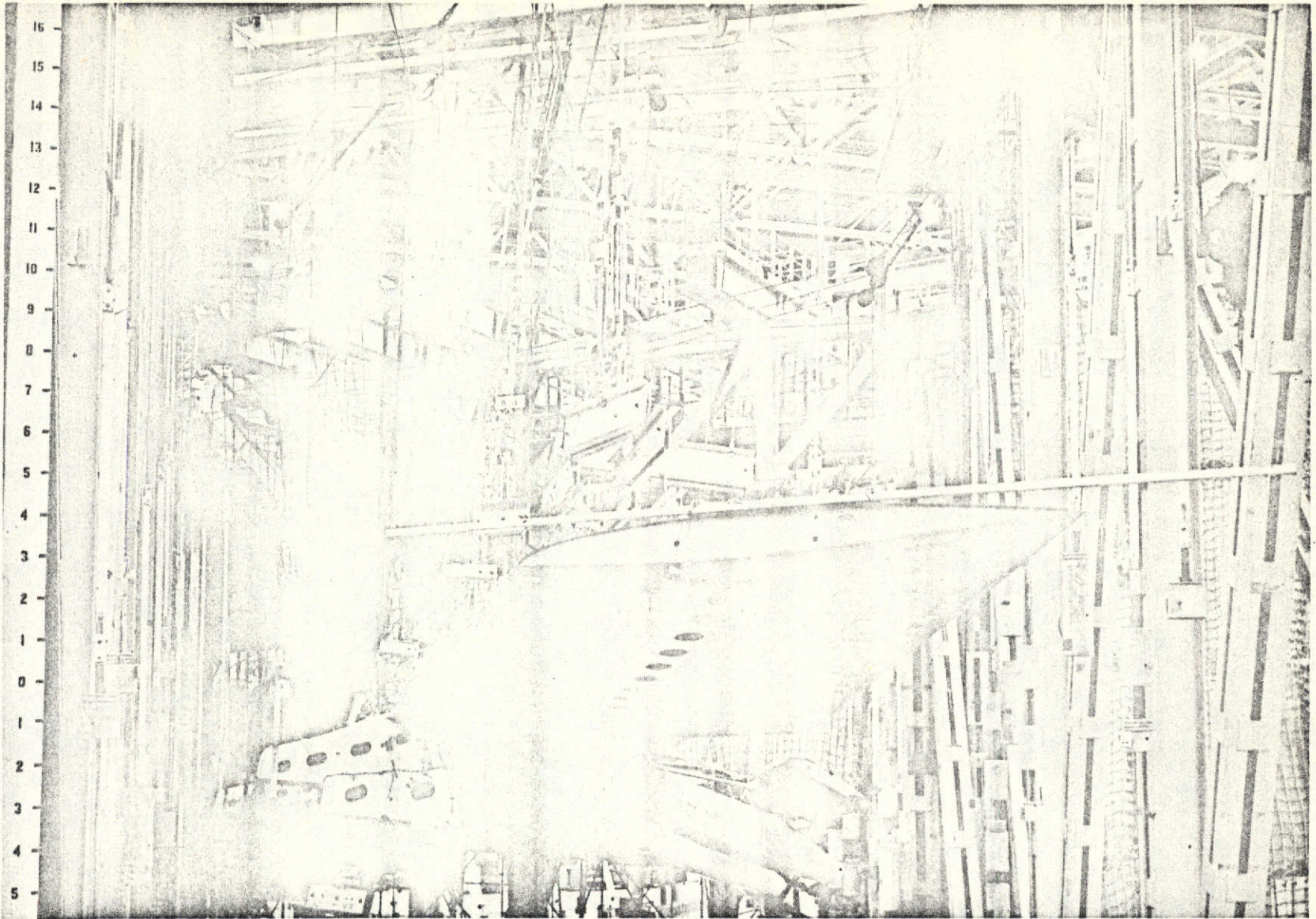
FIGURE 2-3: STATIC TEST SETUP

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2.2.3.3 (Continued)

load condition. When structures are subjected to both load and heat, compression pads are normally used since tensile pad materials may not be suitable at the test temperature.

The system of concentrated load points on a structure are condensed to a single load application through a series of statically determined beams, as is shown in Figure 2-4. This final load point is then connected to (usually) a hydraulic cylinder, a fail safe strap, and a load cell.

Application of shear load is accomplished in a much simpler fashion since the load is applied in the plane of the skin rather than normal to it. A typical application of shear load to an aircraft fuselage is shown in Figure 2-5. Another example of applied shear is shown in Figure 2-6.

In addition to the normal and shear loadings, tank pressures are normally encountered in static testing, however, these pressures require no particular consideration and will not be discussed here.

2.2.3.4 Static Test Temperature Application System - A temperature application system will consist of heating as well as cooling sub systems. The heating subsystem has been historically restricted to radiant heat lamps, heating strips, and forced hot air. Forced hot air heating is described and shown in Reference 6. Radiant heat lamps are applicable for required temperatures on the order of $1000^{\circ}F$ or lower; heat strips may be used up to about $400^{\circ}F$; and hot air systems up to about $300^{\circ}F$. A cooling subsystem will normally consist of a cool forced gas system. Depending upon the cooling required, cryogenic gases or ambient temperature gases may be used.

On occasion, especially in the case of tankage, temperatures are applied through the use of cryogenic fluid.

2.2.4 Static Test Results

Results obtained from static test normally consist of deflection and strain gage recordings. Temperatures and applied loads are also recorded as verification that the specimen is being subjected to the proper environment.

2.2.4.1 Interpretation of Results - Deflections recorded in static tests usually require no special interpretation, however, it is necessary to always understand what deflections are being recorded.

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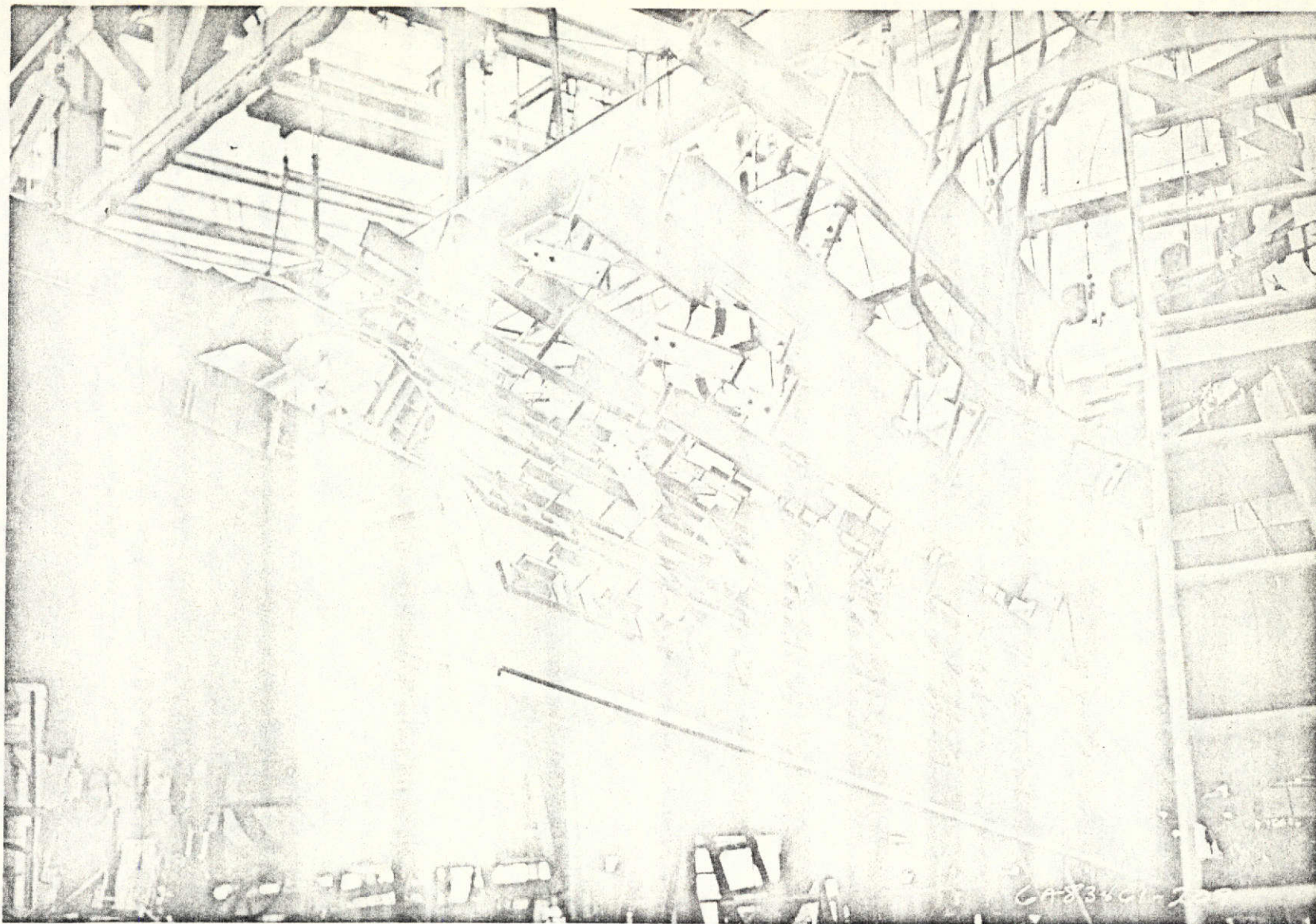
FIGURE 2-4: STATIC LOAD APPLICATION SYSTEM

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FIGURE 2-5:   TYPICAL SHEAR LOAD APPLICATION TO A FUSELAGE
(747 AIRPLANE)

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D5-17269

FIGURE 2-6: S-IC-S SATURN V SHEAR REACTION

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2.2.4.1   (Continued)

For example, the specimen as well as the test fixture are elastic structures
and each contribute to the overall deflected shape.   Strain recording are
not as easily interpreted as deflections since they are susceptible to local
strain risers and material thicknesses.   These gages are usually placed
in anticipated critical locations, however, so that the actual recording in
comparison with nearby recordings is not as important as the magnitude
of the recordings.   Cautious interpretation of gages on thin material is
always warranted since these gages will always be measuring surface
strain.   These recordings, therefore, will contain strain derived from
inplane as well as bending loads.

2.2.4.2   Application of Results - Results from static test are,
of course, used to verify the analytical predictions.   Since stresses (or
strain) are derivable from the deflected specimen in both the test and
analysis, the deflections form a basis for comparing the two.   From
such a comparison, areas in the structural simulation may be judged to
possess the correct amount of stiffness or too much or too little stiff-
ness as the case may be.   This comparison will allow for perfection of
the simulation and for a more accurate description of the specimen stress
levels.

Test load levels sufficient to remove slack in mechanical joints are re-
quired for such a comparison, and usually amount to no more than 50
percent of limit load.   Selected strain recordings usually serve as
backup data in this comparison.

If static tests are performed to limit load level, but preferably higher,
they serve to verify the design, even if failures are detected.   If these
failures are very premature, design modifications are usually made
before proceeding with additional testing.

The maximum load applied in test serves to indicate the minimum capa-
bility of the structure, and if the minimum capability is above the design
load, this minimum represents the minimum growth potential of the
structure.   Further interpretation of the analysis and test results may
justify an even higher growth potential.

2.3   Fatigue Testing

The load environment to which a vehicle is subjected in its lifetime is
composed of a whole spectrum of loads ranging from zero to limit load.
The capability of the vehicle to withstand the highest load from this
spectra is verified in the static loads analysis and test.   It is obvious

2.3   (Continued)

that the vehicle could, therefore, withstand, singularly, any load in this spectra. Such an observation does not, however, take into account the accumulative damaging effect of this spectrum of loads. Such damage is commonly referred to as fatigue damage. The detailed microscopic and metallurgical mechanisms leading to metal fatigue are complicated and not particularly germane to this study. It will suffice to say that fatigue damage is initiated at micro- or macroscopic material flaws and is propagated by repeated loading.

The nature of crack propagation by cyclic loading is so complex that no qualitative analysis approach, either empirical or otherwise, has yet been developed which adequately accounts for all variables. As in static load application, one of the primary variables in cyclic load application is stress level, however, for cyclic loads, many other parameters such as material, part, state of internal stress, stress imposed by test or service conditions and environmental conditions must be included.

The consideration of so many complex variables has prevented any accurate prediction of the fatigue life of a design detail and has relegated the fatigue analysis to merely an indication. Because of the unreliable results of analytical predictions, factors of safety ranging from 2.0 to 4.0 are commonly used and test verification is a must.

2.3.1   Fatigue Load Analysis Procedure

The static loads analysis began after the definition of a load environment; however, the establishment of the fatigue load environment involves significant compromises. A random trace of an actual flight load is reduced to another simplified form, for example, a cumulative distribution of load peaks. The question arises, however, as to whether or not this distribution truly represents the random trace of loads. Several methods in common use for describing random traces of loads are presented in Reference 7.

The basis upon which fatigue damage is assessed in an analysis is embodied in the manner in which the cumulative damage is summed. As previously stated, there is yet no universally accepted theory of cumulative fatigue damage which effectively accounts for all significant parameters; however, there does exist a generally accepted method for predicting cumulative damage which is simple and has shown to give generally conservative results. This method postulates that damages may be summed in a linear fashion, that is, that cumulative damage is given as the linear sum of all partial damages created by

2.3.1   (Continued)

a constant stress occurring for a given number of cycles.   This damage
index, D, is defined as

$$D = \sum_i \frac{n_i}{N_i}$$

where

n_i = Number of cycles occurring at design stress σ_i
N_i = Number of cycles at which failure occurs under stress σ_i

This cumulative damage rule is commonly referred to as the Miner-
Palgren rule and assumes that failure occurs when $D = 1.0$.

Such a procedure as just described implies and requires the existence of
N_i.   This information is contained in a diagram commonly referred to as
an S-N curve or Wholer diagram.   Such a curve defines the relationship
between maximum stress and the number of cycles to failure; it is
generated using a sinusoidly varying load while holding other significant
parameters constant.   These parameters include:

(1)   Mean stress
(2)   Temperature
(3)   Minimum stress

The design stresses used in the cumulative damage are easily derived,
and with sufficient accuracy in most cases, from a finite element or
equivalent analysis.

2.3.2   <u>Fatigue Test Philosophies</u>

Industry has generally accepted two philosophic concepts, "safe-life"
and "fail-safe," in providing structural reliability in aircraft structures.
The concept of safe-life fatigue design demands that no fatigue failure
occurs during the operational life of the structure.   If fatigue does
initiate, a safety problem exists and the service life of the structure
is terminated.   In contrast to safe-life design, the fail-safe fatigue
design concept tolerates the initiation of unanticipated fatigue damage
but requires the detection and subsequent repair before catastrophic
damage does occur.   Hence, fail-safe fatigue design provides safety
through damage containment but trades maintenance cost for the service
life gained beyond the initiation of fatigue damage.   This provides an

2.3.2   (Continued)

indefinite service life limited by economic factors rather than safety.
Obviously, fail-safe structure must have a satisfactory level of fatigue
performance if maintenance is not to become an economic burden. Hence,
a structural reliability through fail-safe design must be supported by an
adequate level of fatigue performance.

2.3.2.1   Fatigue Test Objectives - The structural design of any
space hardware system must have a high degree of structural relia-
bility and safety during the intended service life of the structure. This
objective must be obtained with the lowest possible production cost,
weight, and potential maintenance cost in order to provide the maximum
product operational performance. Therefore, the specific objectives of
fatigue testing are as follows:

(1)   Verify that the fatigue life of a structural design is equal
        to or greater than the actual life times some factor of
        safety.

(2)   Locate fatigue critical areas.

(3)   Provide test data for refining analytical predictions.

(4)   Develop structural inspection and maintenance predictions.

(5)   Evaluate "fail-safe" characteristics of major structural
        components.

2.3.2.2   Fatigue Test Requirements - Fatigue test requirements
generally contain the following items:

(1)   Position restraint

(2)   Loading conditions, including
              (a) Distribution
              (b) Spectra

(3)   Instrumentation

(4)   Inspection

(5)   Maintenance

2.3.2.2   (Continued)

Position restraint in fatigue testing is similar to that required for static testing; however, diligent effort is usually necessary to ensure that no stress concentrations occur because of the specimen support that does not actually exist in the hardware system.

Load conditions specified for fatigue testing are time varying and are therefore specified in the form of a trace or time history of load magnitude.

Instrumentation for fatigue tests generally include strain gages for monitoring critical stresses, crack indicators placed in critical locations, and in some instances S/N Fatigue Life gages for providing fleet inspection information.

Inspection requirements during a fatigue test usually consist of major and minor inspections during the course of testing and a teardown inspection following test.   Major inspections consist of a relatively complete inspection of the test specimen, both internally and externally.   During this inspection, selected hardware is removed and inspected for evidence of wear or fatigue.   During minor inspections, no hardware is removed.   The inspections are accomplished using visual, dye penetrant, and electronic aids required to locate and define fatigue damage.

Although the test article is inspected periodically throughout the course of testing, there are potentially critical areas that are inaccessible by normal inspection procedures and require teardown for proper inspection. The primary objectives of the teardown are to identify, disassemble, and inspect these suspected critical areas after completion of cyclic testing. This will ensure that potential problem areas have not been overlooked.

The teardown consists of dismantling or cutting the selected structural, components into sections, segments, major assemblies and parts.   Care is exercised during disassembly and cutting operations to avoid obscuring damage.   All cutting is done away from splices or other suspected critical areas.   During disassembly, all parts are clearly identified, tagged, and stored for further examination and possible future use.

In all inspection phases, specimens of the fracture faces of significant failures found to occur during the cyclic testing are removed from the test article and submitted for metallurgical examination.   These specimens are examined to determine the material composition and the nature

2.3.2.2 (Continued)

of failure. If the failure is found to contain indications of fatigue, the origins will be identified and an attempt will be made to estimate the time at which cracking initiated and the causative effects.

During fatigue testing, it is recognized as a possibility that fatigue cracking of the test article will occur at various times during the test program. When cracking occurs, testing is stopped for a length of time necessary to design, fabricate, and install repairs on the specimen. Repair of "minor" cracks or fractures in the test article structure are included as part of this effort. Such repairs are suitable for use on the fleet hardware.

2.3.3   Fatigue Test Methods

2.3.3.1   Fatigue Test Article - Test articles used in fatigue tests are structurally very nearly identical to the flight hardware. Alterations of the test specimen, at the very least, alter the stress distribution around the alterations and possibly obscure the results of the fatigue test. For this reason, alterations to a structurally complete test article are held to a minimum. The necessity of keeping stress concentrations to a minimum explains the configuration of the fatigue load application devices. By applying load through compression blocks, the structure immediately adjacent to the load point is placed in compression with the result that fatigue damage at the load application points is minimized.

2.3.3.2   Fatigue Test Setup - The fatigue test setup for the Boeing 747 aircraft is shown in Figure 2-7. This setup on a gross scale is very similar to the static test setup, however, the philosophy in making the test setup is considerably different. This difference is primarily manifested in the degree of permanency planned for the setup. For a large aircraft as shown in Figure 2-7, the setup is expected to remain intact at least two years.

2.3.3.3   Fatigue Load Application System - Even more so than in static testing, applied load in fatigue testing represents a compromise between theoretical prediction and what is practical to achieve. The compromises arise out of the practical limitations of economics and reliability. Economic considerations are tied to the fatigue load control system which is required to regulate the pressure on a hydraulic cylinder in a time-varying manner and to maintain this time-varying pressure in proper sequence with other loading systems. It would appear that as a minimum, the complexity and cost of the load system would increase
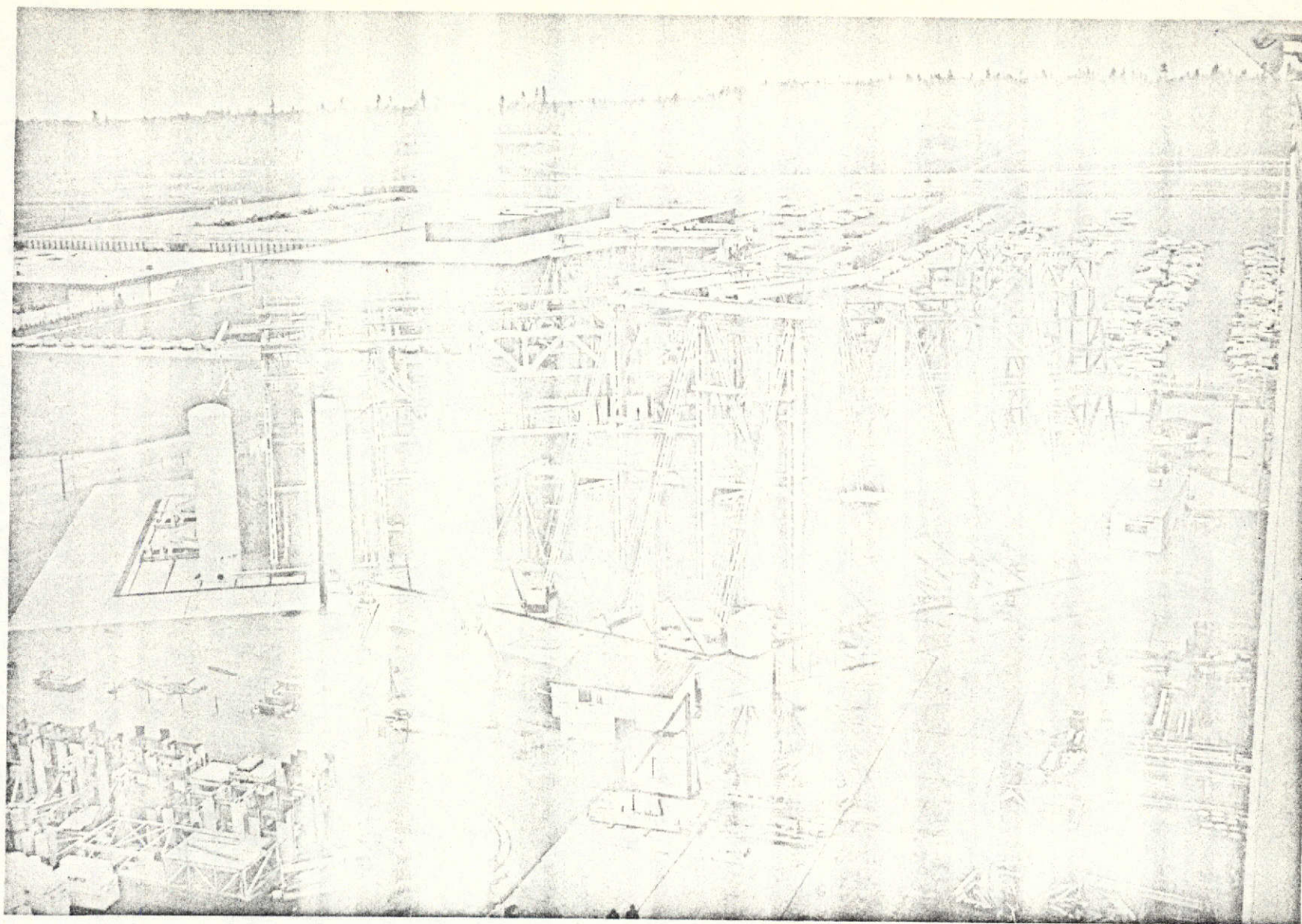
FIGURE 2-7:   FATIGUE TEST SETUP, 747 AIRPLANE

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2.3.3.3   (Continued)

linearly with the number of hydraulic cylinders used in the test.   The
reliability of the loading system is also a very significant consideration
when it is realized that it must last the life of the specimen.   Obviously,
as the number of loading systems increases or as the number of load
points on the specimen increases, more parts are involved and thus the
overall reliability will go down.   The problem of reliability is also
interrelated with the problem of economics, since for a given relia-
bility (or required fatigue life), the design and analysis effort of the
loading system will increase exponentially as the number of load systems
and specimen load points increase.

As in static testing, theoretical load distributions in fatigue testing are
simulated by a distribution of concentrated loads.   These loads are
typically applied through compression pads and because of the cyclic
load, usually occur on opposite faces of a structure (See Figure 2-8).
At first glance, these figures lead one to believe that concentrated loads
are applied as tension; however, it should be noted that in the load systems
shown in Figure 2-8, for example, load applied through a hydraulic
cylinder in tension is transferred to the opposite side of the structure and
reacted via compression pads.   As in the case of static tests, the loads
applied through a hydraulic cylinder is distributed to the structure by a
system of statically determinant beams.   In application of these loads
as well as shear or tension loads, it is necessary to insure that speci-
mens alterations are kept to a minimum.

2.3.3.4   <u>Significant Fatigue Testing Characteristics</u> - There
are two significant characteristics of fatigue testing that should be re-
emphasized.   These are:

(1)   Load amplitude
(2)   Accumulative properties of damage

Because fatigue test loads are intended to simulate a spectra of flight
loads, there are, by nature a large number of applied loads that are
only a fraction of the design limit load.   On occasion, however, loads
on the order of 90 percent of the design load are applied.   These facts
allow for fatigue test fixture designs that are of less strength that
static test fixtures but which, of course, must have far better fatigue
properties.   These load amplitudes also impose less stringent
requirements upon the load application devices from a strength point
of view.

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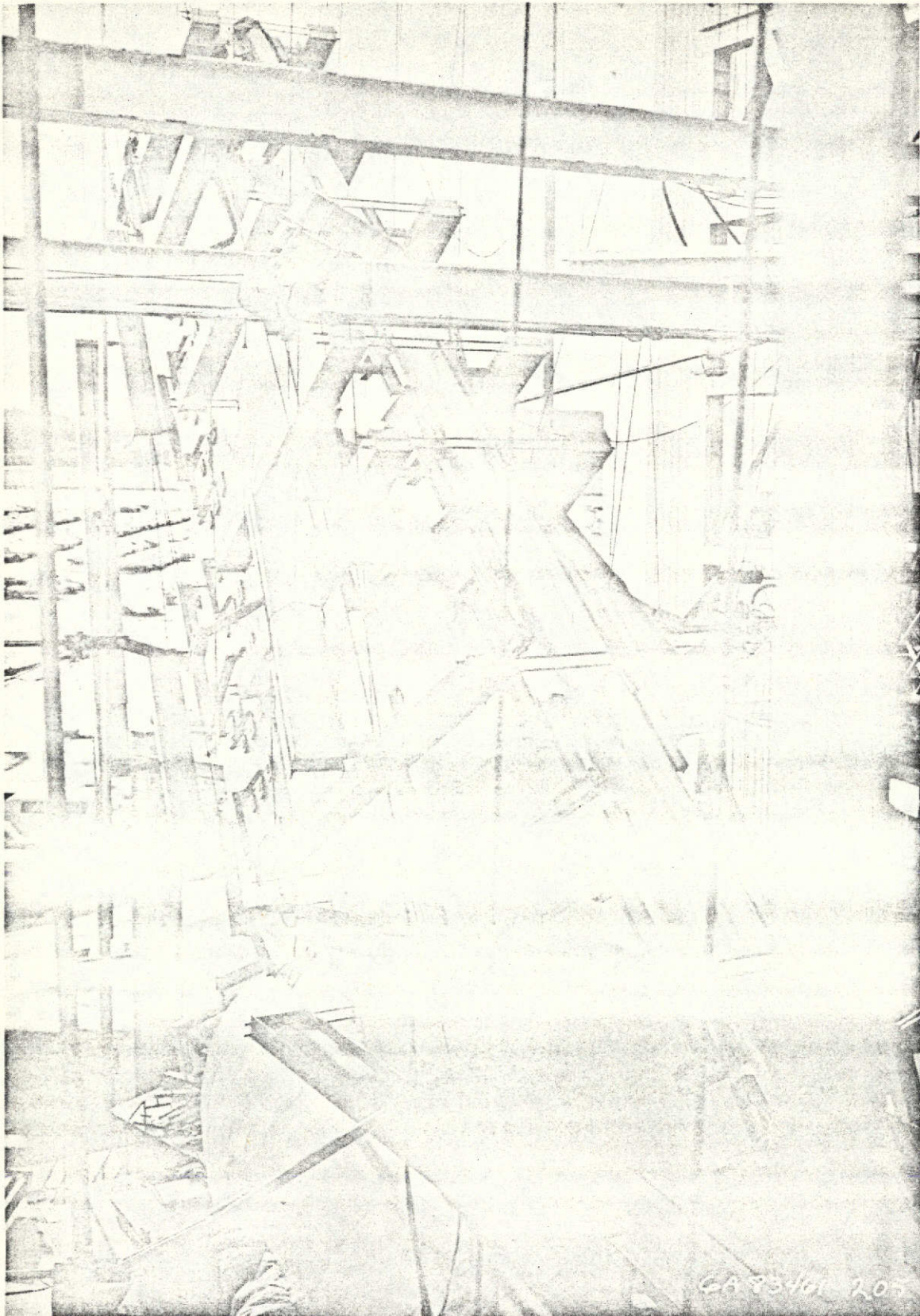
FIGURE 2-8: FATIGUE TEST LOAD APPLICATION - COMPRESSION PADS

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2.3.3.4   (Continued)

Fatigue damage as evidenced by a crack represents an accumulation of incremental damage which by definition is time varying. Therefore, in fatigue testing, results of or conclusions about the tests are usually not available for some time after testing commences. The governing time requirement is that the accumulated number of simulated flights times the appropriate factor of safety shall always be greater than the actual accumulated number of flights for any vehicle in service.

2.3.4   Fatigue Test Results

The results of a fatigue test on a complex structure include simply a manifest of all detected cracks and describes in detail the following:

(1)   Location
(2)   Part containing crack
(3)   Time of detection
(4)   Length of crack

2.3.4.1   Interpretation of Results - A description of cracks from a fatigue specimen bears the same relationship to fatigue testing as strain gage or deflection recordings bear to static testing. In either case, they form the basic raw test data. When visual inspection will not suffice, microscopic and metallurgical examinations are used to define the origin of the crack and to assist the analyst in defining the cause of crack initiation. Using the same information and a fracture mechanics analysis, the analyst is also able to define cracks of a critical length.

2.3.4.2   Application of Results - At the conclusion of a fatigue test, the test specimen is normally subjected to a load approximating 90 percent of limit design load. If the specimen survives this final load application without catastrophic failure, the structural design is judged to be a fail-safe design* and to have met the fatigue life requirements.

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*In many instances, cracks are not always developed which provide for qualification of the fail-safe design. In these cases, artificial cuts are placed in the structure for fail-safe qualification.

2.3.4.2   (Continued)

The results, both intermediate and final, of a fatigue test will serve to identify most fatigue critical areas of the specimen. Depending on the time of detection and degree of severity of the crack, a design modification may be warranted. In any case, the test results will form the basis for most required design changes. The time of detection and location will also form the basis for the inspection procedure of flight hardware.

Finally, the test data are used to refine the stress endurance curves for the actual detail designs being used in the structure. In so doing, the analyst is able to make better fatigue predictions for different applications of the flight vehicle than the test represented, and avoid deficient design details and make better fatigue life predictions on future hardware.

2.4   Problem Areas

In this paragraph, problems associated with major structural testing which can have an important influence on the feasibility of the single test specimen concept are discussed.

2.4.1   Thermal Cycle

In the transition from subsonic to supersonic operations, the major new parameter influencing structural fatigue resistance is elevated-temperature exposure. The new influence on service life, not significantly present in subsonic operation, is the thermal cycle.

The major question is, then, how to include the thermal effects in order to do a meaningful fatigue test. There are a number of significant effects including

    (1)   The thermal stresses produced by heating and cooling.

    (2)   Creep arising from prolonged time at temperature under load.

    (3)   Overageing arising from prolonged time at temperature and giving a reduction of static strength.

    (4)   The interaction of all these thermal effects on each other and on the fatigue behavior of the structure under mechanical loads.

2.4.1 (Continued)

If the thermal stresses are of comparable magnitude to the direct stress, they should not be ignored. They might be simulated by mechanical means, but although this may be feasible in simple specimens, it is not thought to be practicable in the complex structure of a complete airframe. By their very nature, thermal stresses arise from the differential expansion or contraction of adjacent structure and have a varying pattern throughout the structure depending upon the temperature differences set up with time.

2.4.2 Time to Test

It is possible to complete the fatigue tests on a subsonic flight vehicle in an acceptable time; it is sufficient to represent only the stress variations caused by the loading actions so that a test cycle is considerably shorter time than the flight it represented. A flight can be simulated in five (5) minutes. In the case of supersonic flights the problem is much more difficult. Factors associated with temperature and time must be considered-namely those discussed in paragraph 2.4.1.

Real time testing generally makes the total test time unacceptable. A quick look at Figure 2-9 shows what real time testing of fatigue life on a long-life, cruise type aircraft means. We are talking of 10 years, obviously impractical. Also indicated on Figure 2-9 is the amount of compression, 10:1, which gets one down into the practical range of testing. Therefore means to accelerate the test are vital, especially when a single test specimen is to be considered.

2.4.3 Difficulties in Simulating Temperature Environment

The duplication of the true applied loads and temperature on any component, and specially full scale complete airframes, is extremely difficult, complex and expensive. Some of the most important problems are:

(1) Additional time is required to perform the test and increased expenses are incurred by the increase in engineering man-hours and additional equipment required due to elevated temperatures.

(2) Exact loads and temperature environment may not be duplicated accurately enough to justify the additional time and expense.

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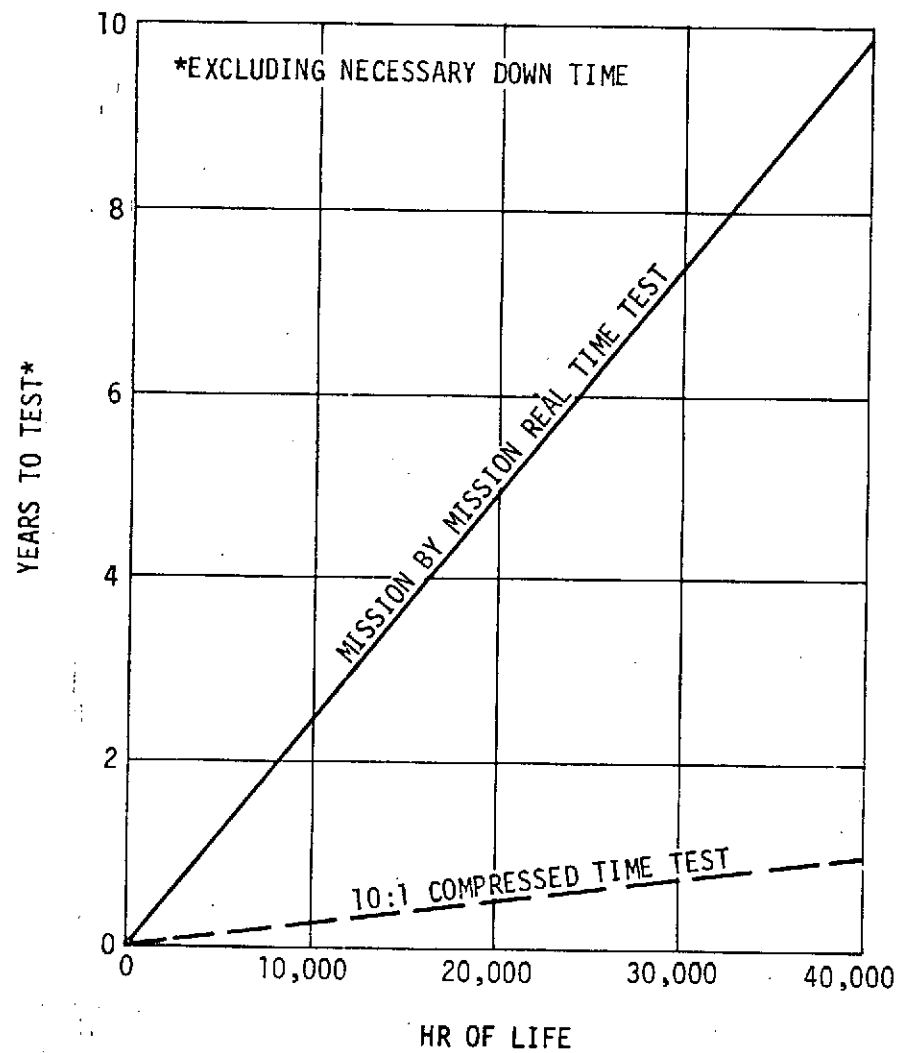
FIGURE 2-9: EFFECT OF TIME COMPRESSION IN ELEVATED TEMPERATURE
FATIGUE TESTING.
REAL TIME VS. COMPRESSED TIME TEST (REF. 8)

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2.4.3 (Continued)

   (3) On large components, the temperature and load applications
       must be made sequentially or simultaneously; in either case
       this necessitates the presence of heating and loading devices
       in the same area simultaneously. Even if this can be done,
       the loading devices (pads, etc.) represent local heat sinks
       of high heat capacity, making it virtually impossible to
       duplicate the structural distribution accurately as would be
       required.

   (4) Since the data obtained from the test is of primary importance,
       the complexity of the elevated temperature simulation is
       expanded considerably by the amount, type, and doubtful
       accuracy of the instrumentation required in such tests.

These difficulties and others such as the vast numbers of thermocouples
required and monitoring the data during the test as a constant check on
the local temperatures and temperature distributions, forced many con-
tractors to perform major tests, and specially static tests, at room
temperature using additional factors on the applied loads. These applied
load ratios are established by some rational procedure which allows for
material property variation and the presence of temperature induced
load (thermal stresses).

2.4.4   Feasibility of Simulating Elevated Temperature Static Tests
         @ R. T.

An analytical-experimental program (Reference 9) used simple box beam
structures loaded in bending or compression to verify the feasibility of
simulating elevated temperature static tests at room temperature. Test
and analysis data for room temperature, and for symmetrically and
unsymmetrically heated box beam structure under static loads indicated
that the effects of material properties degradation and thermal stresses
could be accounted for analytically by using strain analysis procedures
which allowed the construction of load-deformation curves for the critical
cross-section. The comparison of the curves for room temperature with
those of any other temperature environment provided the applied load
ratios for yield load, ultimate load and for any other desired value of
permanent set. Analytical-experimental comparison, using critical
element strain gage data versus calculated strains, indicated this approach
was feasible.

A verification program was then instituted to perform similar studies on
full-scale aircraft components (Reference 10). The results of the study

2.4.4   (Continued)

supported the use of applied load ratios for room temperature simulation
of elevated temperature static tests within the limitations of the analy-
tical methods.   The accuracy to be expected for bending tests is shown
to be within ± 10% based upon the failing load comparison, but depends,
to a large extent, on the accuracy of the basic material properties.   In a
multiplate, multi-fastener splice joint the accuracy demonstrated was
shown to be ± 16%.

There are limitations involved with the use of the applied-load-ratio
method.   It is now applicable to aircraft structure which fail in bending
and/or axial load, under steady-state elevated temperature environments.

2.5   Test Time Compression - Elevated Temperature Fatigue Testing

A method of compressing the elevated temperature fatigue test time of
supersonic aircraft, while maintaining the true time damage level is
presented in Reference 11.   The scope of the study was to develop a
general test time compression (TTC) method applicable to a wide range
of supersonic aircraft having maximum speeds from M = 2.0 to M = 5.0
and total lives between 5,000 and 50,000 hours.   For this speed regime,
peak skin temperatures range from 121°C (250°F) to 537°C (1000°F).

The problem is approached by dividing the mission into the following
three regimes:

    (1)   Subsonic - no temperature effects

    (2)   Moderate temperature - where fatigue damage is influenced
                                  by thermal stresses

    (3)   Elevated temperature - where both thermal stresses and
                                  creep phenomena significantly
                                  modify fatigue damage.

In the subsonic regime, currently used test time compression (TTC)
methods are applicable; namely, consisting of eliminating all load cycles
below a given amplitude, and the time periods between the cycles.   At
times a large number of low amplitude cycles are replaced with a smaller
number of high amplitude cycles causing equal fatigue damage.

In the moderate constant and variable temperature regimes, the assump-
tion is made that creep is not significant so that the TTC criteria of the

2.5   (Continued)

subsonic regime may be applied, with the addition of true time heating and cooling to induce the proper thermal stresses (See Figure 2-10 and 2-11).

In the elevated constant temperature regime the load cycles are applied under true time temperature conditions with the time between load cycles eliminated.   The effects of eliminating the time between load cycles is compensated for by raising the temperature to increase the rate of creep and by adjusting the steady stress to simulate the creep strain and the degree of metallurgical instability in true time mission (See Figure 2-12).

In the elevated variable temperature regime, the temperature is raised and the steady stress is adjusted to simulate the true time rate of creep and the degree of true time metallurgical instability, while the alternating load stress is adjusted to simulate the fatigue damages.   (See Figure 2-13).

Two alternates were also investigated. The first alternate, is to assume a capability to control the temperature of both inner and outer surfaces during cycling to get the desired value of thermal stresses. The second alternate, and probably the most realistic one for full-scale testing is to have an inner surface temperature control. For this alternate, heating and cooling is provided in true time for only as many cycles as are required for superposition of the required load cycles. The damage due to the remaining thermal cycles and the creep occurring during the time between load cycles are simulated at a predetermined number of locations using steady state temperature gradients and rapid load cycles in conjunction with increased temperatures and modified mean stresses based upon a form of creep diagram developed for the analysis.

Utilizing the general procedures outlined in Reference 11, the investigators analytically developed time compression ratios of from 9 to 18 on a representative Mach 3.2 vehicle.

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BASIC ENVIRONMENT   COMPRESSED BASIC ENVIRONMENT

OUTER SKIN TEMP. $-----T_t$ OUTER SKIN TEMP. $----T_c = T_t$

LOAD P_o LOAD

$\cong$
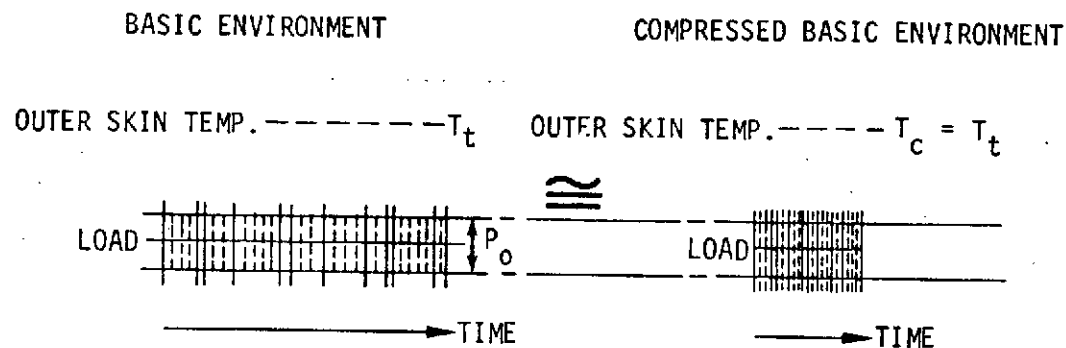
TIME   TIME

1. ELIMINATE TIME BETWEEN LOAD CYCLES.

2. REPLACE LOW AMPLITUDE LOAD CYCLES ($P_t<P_o$) WITH FEWER HIGHER
   AMPLITUDE CYCLES ($P_c>P_o$) TO PRODUCE EQUIVALENT DAMAGE.
   P_o IS AN ARBITRARY LOAD CUT OFF, BELOW WHICH ONLY A SMALL PERCENTAGE
   OF THE FATIGUE DAMAGE OCCURS.

FIGURE 2-10: TEST TIME COMPRESSION CRITERIA FOR MODERATE CONSTANT TEMPERATURE REGIME (REF. 11)

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BASIC ENVIRONMENT COMPRESSED BASIC ENVIRONMENT
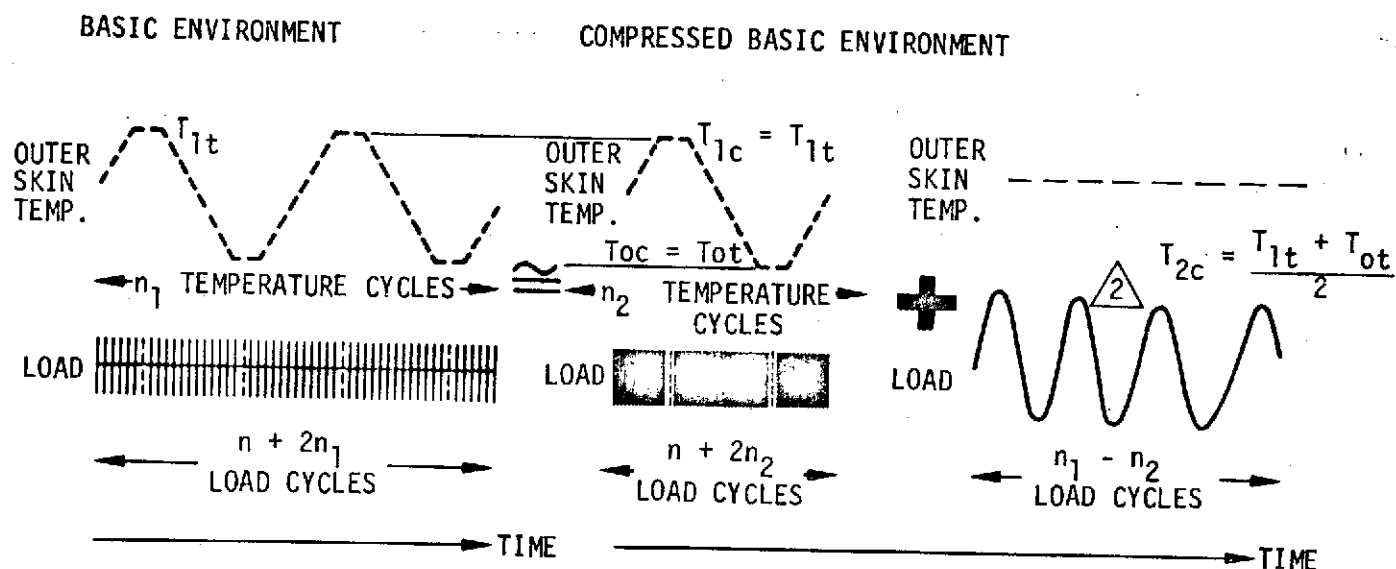
1. APPLY ENOUGH TEMPERATURE CYCLES TO ACCOMMODATE ALL LOAD CYCLES.

2. APPLY ADDITIONAL LOAD CYCLES OF SUCH MAGNITUDE AS TO
PRODUCE DAMAGE EQUIVALENT TO DAMAGE MISSING IN STEP 1.
ONE LOAD PER TEMPERATURE PEAK IS SHOWN DASHED FOR CLARITY.

3. T_{ot} AND T_{1t} ARE MINIMUM AND MAXIMUM TRUE TIME TEMPERATURES.

FIGURE 2-11: TEST TIME COMPRESSION CRITERIA FOR MODERATE VARIABLE TEMPERATURE REGIME
(REF. 11)

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BASIC ENVIRONMENT   COMPRESSED BASIC ENVIRONMENT

OUTER SKIN   OUTER SKIN
TEMP. T_{1t} TEMP. $T_{1c} = T_{1t}$ $T_{2c} > T_{1t}$

$\cong$

LOAD   LOAD

← n CYCLES →   n CYCLES
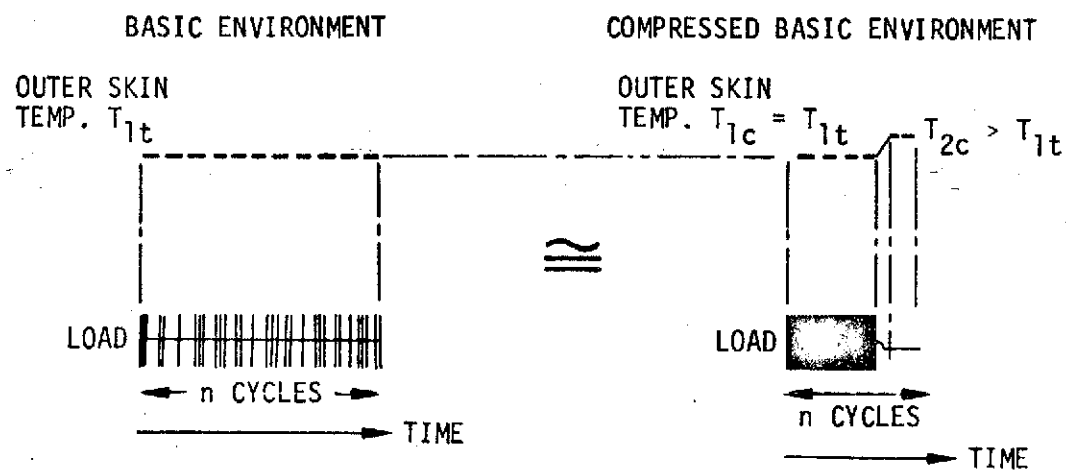
TIME   TIME

1. ELIMINATE TIME BETWEEN LOAD CYCLES. APPLY ALL LOAD CYCLES IN ONE BLOCK AT $T_{1t} = T_{1c}$.
2. COMPRESS TIME DURING WHICH NO LOAD CYCLES ARE APPLIED BY RAISING TEMPERATURE AND MODIFYING STEADY LOAD.

FIGURE 2-12: TEST TIME COMPRESSION CRITERIA FOR ELEVATED CONSTANT TEMPERATURE REGIME (REF. 11)

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BASIC ENVIRONMENT

n_1 TEMPERATURE CYCLES

OUTER SKIN TEMP. T_{ot}

T_{1t}

$\Delta\alpha$

LOAD

←n+2n_1 LOAD CYCLES→

TIME

COMPRESSED BASIC ENVIRONMENT

n_1 TEMPERATURE CYCLES

OUTER SKIN TEMP.

$\Delta\beta$

T_{1c} T_{1t}

T_{oc} T_{ot}

$\cong$ $\beta > \alpha$

$(T_{1c}-T_{oc})$ $(T_{1t}-T_{ot})$

LOAD

←n+2n_1 LOAD CYCLES→
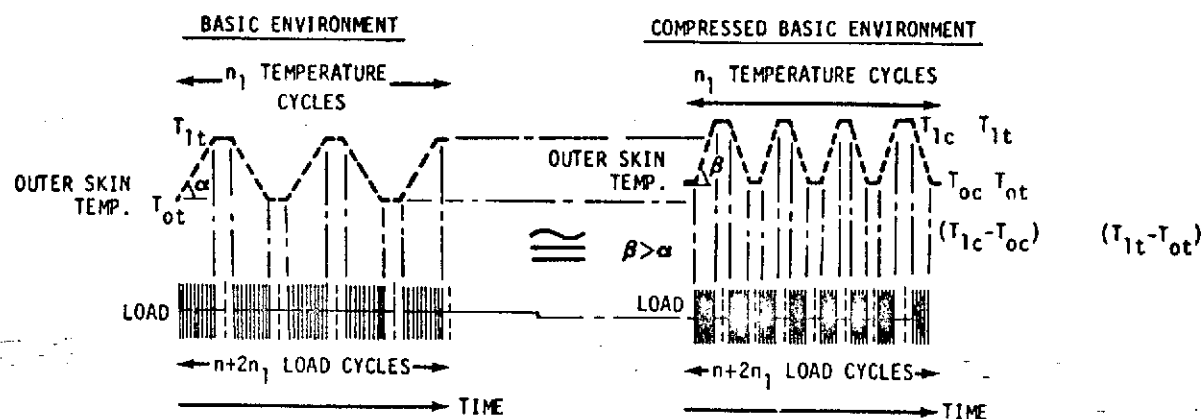
TIME

BASIC CRITERIA

1. INCREASE MAXIMUM TEMPERATURE AND HEATING AND COOLING RATES AND MODIFY LOADS.

2. DECREASE TEMPERATURE RANGE TO PRODUCE TRUE TIME THERMAL STRESSES.

ALTERNATE CRITERIA

1. APPLY ENOUGH TEMPERATURE CYCLES TO ACCOMMODATE ALL LOAD CYCLES.

⟨2⟩ RAISE TEMPERATURE TO T2c AND MODIFY STEADY LOADS.

⟨3⟩ APPLY ADDITIONAL LOAD CYCLES OF SUCH MAGNITUDE AS TO PRODUCE DAMAGE EQUIVALENT TO DAMAGE MISSING IN STEP 1.

n_2 TEMPERATURE CYCLES

OUTER SKIN TEMP. T_{ot}

T_{1t}

$\Delta\alpha$

LOAD

n + 2n_2 LOAD CYCLES

OUTER SKIN TEMP.

T_{2c}

⟨2⟩

⟨3⟩

LOAD

$n_1 - n_2$ LOAD CYCLES

TIME

ALTERNATE CRITERIA

(TO BE USED IF TEST TECHNIQUES PRECLUDE TEMPERATURE CONTROL OF INTERIOR SURFACES)
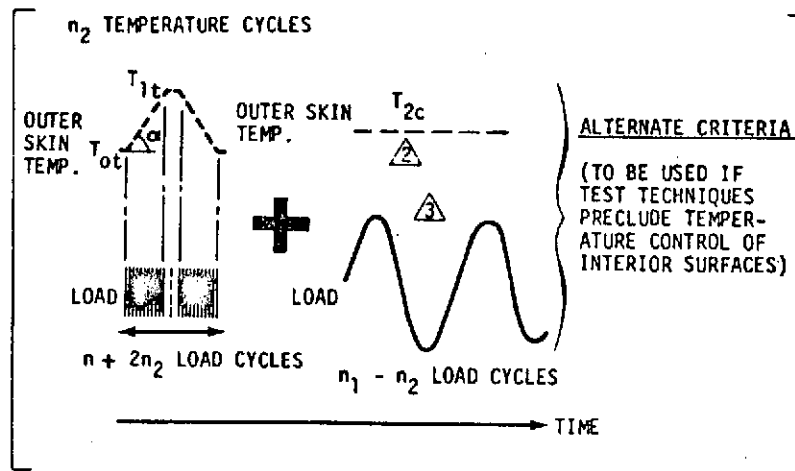
FIGURE 2-13:   TEST TIME COMPRESSION CRITERIA FOR ELEVATED VARIABLE TEMPERATURE REGIME (REF. 11)

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SECTION 3

PARAMETERS AFFECTING FATIGUE LIFE

3.1   Cyclic Load-Static Load Material Interactions

Schijve in Reference 12 has discussed in considerable detail the effects
of several parameters on fatigue life.   This reference will form the basis
of discussion for Paragraphs 3.1.1 through 3.1.3, which deals with the
various loading parameters affecting fatigue life.   In this discussion,
reference will be made to Taylor's Gust Spectrum which is discussed in
detail in Reference 13 and shown here in Figure 3-1, as reproduced from
Reference 12.   Other data from Reference 12 which will subsequently be
discussed is shown in Figures 3-2 through 3-5.   In these figures, the
following notation is observed.

$$S_a \quad = \quad \text{stress amplitude}$$

$$S_m \quad = \quad \text{mean stress amplitude}$$

$$S_E \quad = \quad \text{endurance limit}$$

$$\Sigma n/N \quad = \quad \text{point of failure using linear damage rule}$$

3.1.1   The Effect of Very Low Stress Amplitudes

The linear cumulative damage rule predicts that stress amplitudes below
the endurance limit ($S_a < S_E$) will not contribute to $\Sigma(n/N)$ since $N = \infty$.
A comparison of test series 10, 11 and 15 for 7075 and test series 21 and
25 for 2024, see Figure 3-2, shows that such low stress amplitudes have
an unfavorable effect on the fatigue life.   The same trend in program tests
has been found by other investigators (See Reference 14).   The decrease in
fatigue life due to including low stress levels is not predominantly due
to the crack-propagating effectiveness of these levels, but more import-
antly due to their ability to cause relaxation of the beneficial compressive
residual stress field.   In the absence of an effective residual stress field,
low stress levels are found to be relatively unimportant.   Negative loads
of sufficient magnitude and frequency which eliminate the favorable
residual stresses appear to reduce substantially the effect of low stress
levels, and the necessity of including them in a fatigue test is substantially
minimized.

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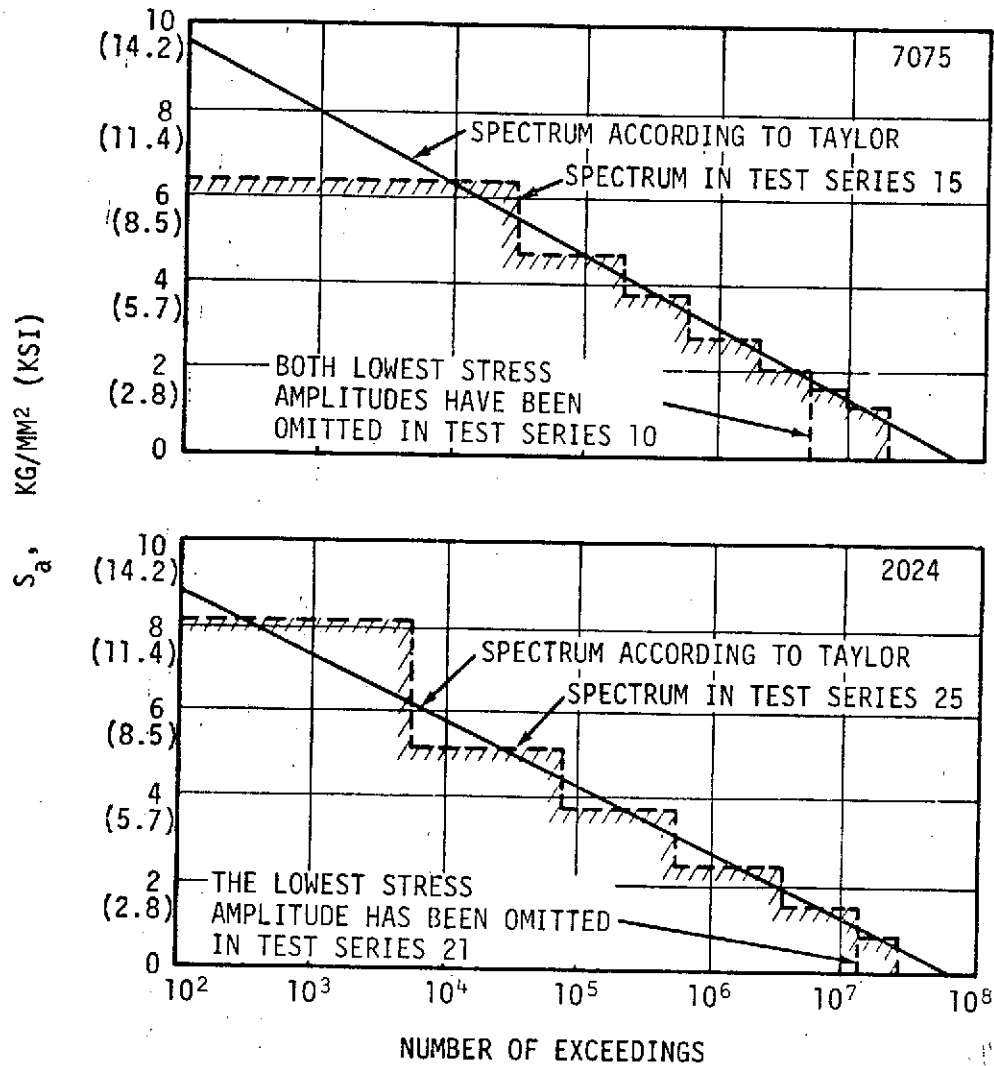
FIGURE 3-1: STRESS AMPLITUDE SPECTRUM ACCORDING TO TAYLOR AND STEPPED SPECTRUM IN PROGRAM TESTS

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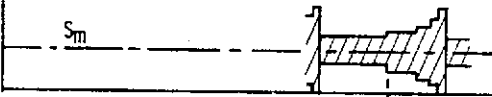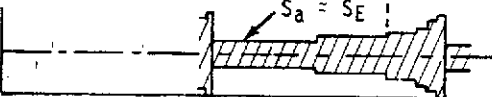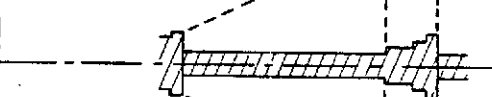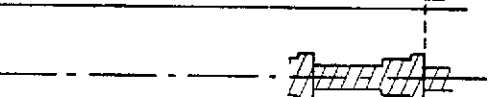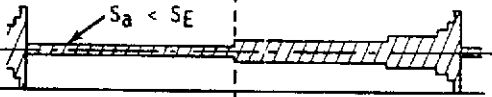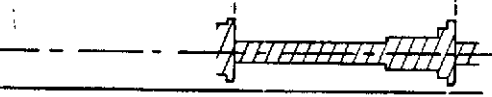
MATERIAL	TEST SERIES	TYPE OF SPECTRUM	SIMILARITY WITH OTHER TEST SERIES	$\Sigma \frac{n}{N}$
.7075	10		TAYLOR'S GUST SPECTRUM, SEE FIG. 3-1	1.08
	11	$S_a = S_E$	SIMILAR TO SERIES 10, ONE LOWER S_a ADDED	0.91
	15	$S_a < S_E$	SIMILAR TO SERIES 10, TWO LOWER S_a'S ADDED SEE FIG. 3-1	0.55
	4		SIMILAR TO SERIES 10, HIGHEST S_a OMITTED AND LOWEST S_a EXTENDED THREE TIMES	0.59
	3		SIMILAR TO SERIES 10, HIGHEST S_a OMITTED AND THE HIGHEST S_a BUT ONE EXTENDED THREE TIMES	0.87
	2		SIMILAR TO SERIES 10, TWO HIGHEST S_a'S OMITTED	0.71
7075	18		TAYLOR'S GUST SPECTRUM. SIMILAR TO SERIES 10, PERIOD LENGTH INCREASED TWICE.	0.76
	1		SIMILAR TO SERIES 18, HIGHEST S_a OMITTED	0.76
2024	21		TAYLOR'S GUST SPECTRUM, SEE FIG. 3-1	2.90
	25	$S_a < S_E$	SIMILAR TO SERIES 21, ONE LOWER S_a ADDED, SEE FIG. 3-1	1.96
	24		SIMILAR TO SERIES 21, HIGHEST S_a OMITTED.	1.31

FIGURE 3-2: THE EFFECT OF THE TYPE OF SPECTRUM ON THE ENDURANCE

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3.1.2   The Effect of High Stress Amplitudes

In this paragraph high stress amplitudes are supposed to be of the order of magnitude of the mean stress ($S_a \simeq S_m$).   For 7075 the results of test series 10, 4, 3 and 2 and also test series 18 and 1 and for 2024 the results of test series 21 and 24 (see Figure 3-2) give the impression that omission of the highest stress amplitudes implies a reduction of the relative fatigue life.   It is believed that at the highest stress amplitude, favorable internal stresses and strain hardening are built up most regorously and the crack growth (or damage growth) at lower stress amplitudes will be slowed down by this action.   Omitting the highest amplitude involves a decrease of the favorable effect.

3.1.3   The Effect of Very High Periodic Loads

Test series have been performed with one high pre-load, periodic high positive load amplitudes, periodic high negative load amplitudes and periodic high complete load cycles.   From the test results shown in Figure 3-3 the following conclusions may be drawn.

One high pre-load increases the fatigue life only to a limited extent. However, periodic high positive loads, though smaller than the pre-load, increase the life considerably; compare test series 10, 5 and 6.   A comparison of test series 6 and 6b shows that if a high load is applied after each two periods instead of one, the favorable effect is appreciably less.   The explanation of this effect is probably two-fold: (1) The internal stresses may decrease during fatigue testing and they are restored again by the periodic high loads.   (2) Microcracks may have formed.   Their growth will be retarded by the internal stresses built up around these cracks by the periodic high loads.   Both reasons may be effective.

With respect to the first argument an interesting comparison is possible between test series 6 and 17.   The same high positive loads were applied in both test series; however, the program loading consisted of increasing amplitude levels in the first test series, whereas a decreasing order has been used in the second one.   The reversal of this order has resulted in a 3 to 4 times shorter life.   It is believed that the higher stress amplitudes, which in test series 17 follow immediately the periodic high loads, are more effective in destroying the favorable internal stress system and thus enable lower stress amplitudes which follow later in the period to become more damaging.   In test series 6, however, the low stress amplitudes follow directly the periodic high loads and are therefore more or less ineffective in that test series.
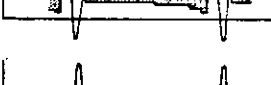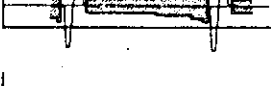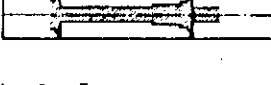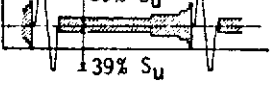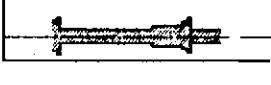
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MATERIAL	TEST SERIES	TYPE OF SPECTRUM $\rightarrow$ TIME	SIMILARITY WITH OTHER TEST SERIES	$\sum \frac{n}{N}$
7075	10		TAYLOR'S GUST SPECTRUM	1.08
	5	$75\% S_u$, $S_m = 20\% S_u$	ONE HIGH PRE-LOAD SPECTRUM OF SERIES 10, HIGHEST S_a OMITTED.	1.42
	6	$39\% S_u$	SPECTRUM OF SERIES 5, ONE HIGH POSITIVE LOAD AT THE END OF EACH PERIOD.	9.90
	6a		SIMILAR TO SERIES 6, HOWEVER HIGH LOADS OMITTED AFTER $\sum N/n=4.65$ (50TH PERIOD).	5.51
	6b		SIMILAR TO SERIES 6, HOWEVER HIGH LOADS AT THE END OF ODD NUMBERED PERIODS ONLY.	3.68
	17		SIMILAR TO SERIES 6, HOWEVER SPECTRUM IN REVERSED ORDER.	2.72
	7	$39\% S_u$	SIMILAR TO SERIES 6, HOWEVER HIGH NEGATIVE LOADS INSTEAD OF HIGH POSITIVE LOADS.	0.51
	8		SIMILAR TO SERIES 6, HIGH POSITIVE LOADS NOW FOLLOWED BY HIGH NEGATIVE LOADS.	0.70
	9		SIMILAR TO SERIES 8, HIGH LOADS IN REVERESED ORDER.	3.11
2024	21		TAYLOR'S GUST SPECTRUM	2.90
	27	$39\% S_u$ / $39\% S_u$	SIMILAR TO SERIES 21, ONE HIGH POSITIVE AND NEGATIVE LOAD AT THE END OF EACH PERIOD.	1.10
	24		TAYLOR'S GUST SPECTRUM, SIMILAR TO SERIES 21, HIGHEST S_a OMITTED.	1.31
	28		SIMILAR TO SERIES 24, ONE HIGH NEGATIVE AND POSITIVE LOAD AT THE END OF EACH PERIOD.	7.76

FIGURE 3-3:   THE EFFECT OF SEVERAL TYPES OF HIGH LOADS ON THE ENDURANCE UNDER SPECTRUM LOADING

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3.1.3   (Continued)

Test series 7 shows that high negative loads have a detrimental effect
on the fatigue life.   A comparison of test series 6, 9, 18 and 7 for 7075
shows that the last half cycle of the complete cycle has a dominating
effect.   The same trend is found for 2024 by comparing test series 27
with 27 and 28 with 24.

3.1.4   The Effect of the Order of Stress Amplitudes

It will have been noted that in most test series discussed until now the
stress amplitudes were applied in an increasing order of magnitude.
A different order might yield other results.   Test results in this res-
pect are shown in Figure 3-4.   For 7075 the effect of different sequences
was not very large - Σ (n/N)-values did not deviate very much from 1.
For 2024 there was a clearly noticeable effect, the highest endurances
being obtained by increasing stress levels.

It is felt that here the same explanation is valid as given before in para-
graph 3.1.2 and 3.1.3 which was based on the formation of favorable
internal stresses and strain-hardening at the higher stress levels, which
are not so easily eliminated at subsequent low stress amplitudes.   It is
not strange that this effect is only found for 2024 material, since the
maximum stress in these tests was 17 kg/mm^2 (24.2 ksi), compared
with 12.6 kg/mm^2 (17.9 ksi) for 7075 material.   Moreover, the yield
stress is markedly lower for 2024 than for 7075.

3.1.5   The Effect of the Period Length

The length of the period is another parameter in conducting program tests.
Tests were performed on 7075 material only.   The ratio of the period
lengths used is 4 : 2 : 1, see Figure 3-5.   A slight influence on the
endurance is found.   The differences do not show an expected or easily
explicable trend.

From the results in this and the previous paragraph it will be clear that
the existence of a unique fatigue life under program loading, depending
only on the applied spectra, is more or less a fictitious idea.   This
does not imply that program tests cannot yield valuable information on
life expectancies.   However, it should be kept in mind that there are a
lot of parameters in planning a program test which might affect the
test result.
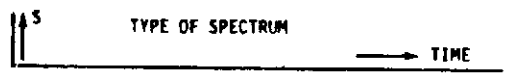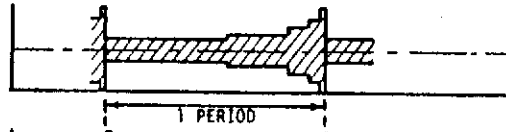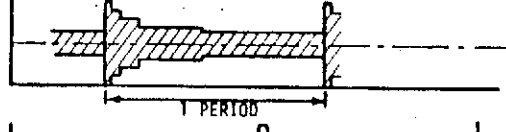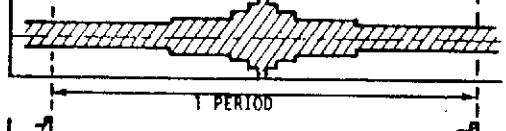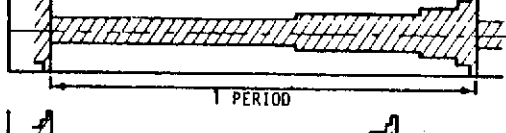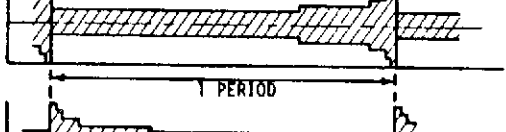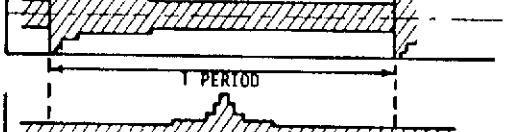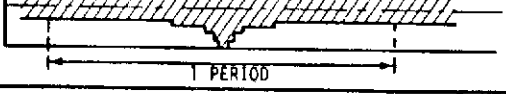
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MATERIAL	TEST SERIES	TYPE OF SPECTRUM → TIME	SIMILARITY WITH OTHER TEST SERIES	$\Sigma \frac{n}{N}$	MEAN LIFE IN PERIODS
7075	12	1 PERIOD	TAYLOR'S GUST SPECTRUM INCREAS-ING S_a.	0.88	19
	13	1 PERIOD	SIMILAR TO SERIES 13, HOWEVER DE-CREASING S_a.	0.84	18
	14	1 PERIOD	SIMILAR TO SERIES 12 AND 13, HOWEVER INCREASING AND DE-CREASING S_a. PERIOD LENGTH TWICE AS LARGE.	0.84	9
	10	1 PERIOD	SIMILAR TO SERIES 14, HOWEVER IN-CREASING S_a.	1.02	12
2024	21	1 PERIOD	TAYLOR'S GUST SPECTRUM INCREAS-ING S_a.	2.90	31
	22	1 PERIOD	SIMILAR TO SERIES 21, HOWEVER DECREASING S_a.	1.56	17
	23	1 PERIOD	SIMILAR TO SERIES 21 AND 22, HOW-EVER INCREASING AND DECREASING S_a.	2.13	25

FIGURE 3-4:   THE EFFECT OF THE ORDER OF SUCCESSION OF THE LOAD-STEPS ON THE ENDURANCE UNDER SPECTRUM LOADING

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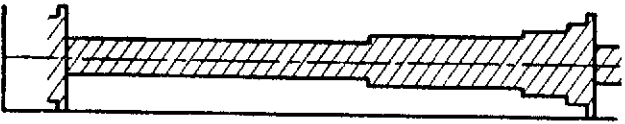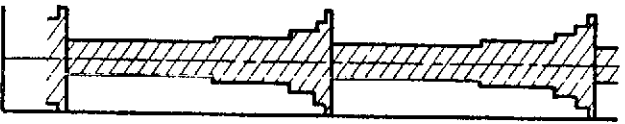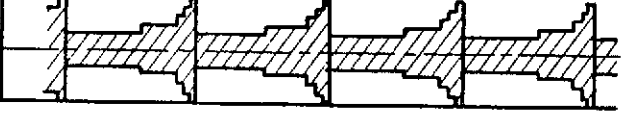
MATERIAL	TEST SERIES	S ↑ TYPE OF SPECTRUM → TIME		SIMILARITY WITH OTHER TEST SERIES	$\sum \dfrac{n}{N}$	MEAN LIFE IN PERIODS
7075	18			TAYLOR'S GUST SPECTRUM	0.76	5
	10			SIMILAR TO SERIES 10, PERIOD LENGTH REDUCED TWICE.	1.08	12
	12			SIMILAR TO SERIES 10, PERIOD LENGTH REDUCED 4 TIMES.	0.88	19

FIGURE 3-5: THE EFFECT OF THE LENGTH OF THE PERIOD ON THE ENDURANCE UNDER SPECTRUM LOADING

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3.1.6 Concluding Remarks

On the basis of the above discussion, the following conclusions seem to be appropriate

(1) For notched light alloy specimens loaded in program fatigue tests at positive mean stresses the fatigue life expressed as $\Sigma (n/N)$ will in general give values of about unity or higher.

(2) Fatigue loads below the endurance limit have a damaging effect; therefore, truncation of low loads from the loading spectrum will have an unrealistic beneficial effect on the fatigue life. This does not invalidate the first conclusion.

(3) The less frequent high fatigue loads in a program fatigue test have a beneficial effect on $\Sigma (n/N)$; therefore, truncation of high loads from the loading spectrum will have an unrealistic nonbeneficial effect on fatigue life.

(4) Periodic very high positive loads have a highly beneficial effect on $\Sigma (n/N)$.

(5) The period length and the load sequence in a program fatigue test have some influence on the fatigue life.

3.2 Program and Random Loading

If a structure encounters irregularly varying loads during service, the foremost problem in life analysis is the evaluation of cumulative damage effects. Cumulative damage studies are concerned with the question of how the partial damages caused by different stress excursions in an irregularly varying stress sequence may be summed up to represent the same damage as may occur in service. The simplest way of solving the problem of cumulative damage would be to perform fatigue tests in which the service-load trace would exactly be copied with respect to sequence, magnitude and frequency of occurrence of the different stress excursions. Until a few years ago, when servo-valve-controlled testing equipment became available, such service load tests could not be performed at all or not in an economical manner. This situation, however, has changed and today service-load testing and other types of random-load testing are more and more often used for a cumulative damage analysis.

3.2   (Continued)

The older approaches to the cumulative damage problem are program testing and cumulative damage hypotheses. While the latter will not be discussed here, program testing will be compared with random testing.

Today, considering the five damage parameters-life, crack-initiation time, crack-propagation rate, failure location, and scatter-the main question is whether program testing gives an identical life compared with the real service life or a life value to which a constant correlation factor can be applied. This question is at present doubtful and requires further discussion, however, this question was studied in detail in Reference 15 and is summarized in Figure 3-6.

The upper load sequence shown in Figure 3-6 is a random sequence of maxima and minima stresses that were applied to a notched specimen. The other load sequences shown represent various other distributions which according to the linear cumulative rule should give the same fatigue for the notched specimen. For these sequences, $\Sigma n/N = 2.7$. The random sequences of stress cycles differs from the random sequence of maxima and mimima in that each positive stress peak is followed by a negative stress peak of equal magnitude as referenced from the mean stress. Other distributions are described in the figure.

Based on Reference 15, the following conclusions are drawn:

(1)   In these tests, program testing leads to an unsafe cumulative damage analysis. Life is overestimated for instance by a factor of about 6.

(2)   If the GAG* cycle is considered in conventional 8-step-program testing, this leads to an unsafe cumulative damage analysis. A specific flight-per-flight test, however, will result in shorter lives than the tests with the random sequence of maxima and minima and randomly interspersed GAG cycles.

---

*Ground-Air-Ground

time history pattern	details	normalized life
	random sequence of maxima and minima	1
	random sequence of stress cycles	0.9
	flight-per-flight program test (loading scheme A)	0.8
	flight-per-flight program test (loading scheme A*)	1.6
	9-step program test with included GAG-cycles and a special test for taxiing load (loading scheme L)	4.1
	conventional 8-step program test with included GAG-cycles (loading scheme H)	6.8
	single cycle flight test (highest gust load occuring once per flight combined with lowest taxiing load occuring once per flight)	11.2
life estimation using Miners-rule		2.7

FIGURE 3-6:   RESULTS FROM DIFFERENT TEST SEQUENCES

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3.3   Temperature Effects

Phenomena such as fatigue, creep, stress corrosion, embrittlement, and delayed fracture (static fatigue), acting alone or in combination, are all damaging to structural materials. The damaging effect of each will vary as often as the conditions of service are altered. The severity of the effects are dependent upon the temperature range imposed, the subjected material, and, most importantly, the duration and frequency of exposure. Applications of changing temperature environments not only result in continuously modifying the basic material properties (E, F_{TY}, F_{TU}, etc.) and thermal stress patterns, but can also introduce the following effects:

(1)   Precipitation aging of certain alloys occurs if the material is maintained at high temperatures for sustained time periods either with or without the presence of stress; thereby, embrittling (decreasing ductility) the material to the extent that its ability to sustain additional load sequences can be significantly reduced.

(2)   Depending on the maximum temperature imposed, stress magnitude, and time of exposure, increased material creep deformations can occur which, if omitted during service life computations, will result in erroneous conclusions in predicting fatigue life.

(3)   High and low temperatures have significantly different effects on the initiation and propagation of cracks at stress concentrations. At high temperatures, localized stresses are relieved by strain in the form of material grain boundary slip which if repeatedly induced can lead to fatigue crack formations and their advancements. At low temperatures, the material is less ductile and local stresses tend to build up because of the resistance to grain boundary slippage. If this resistance is sustained, high local stresses develop and are relieved, not through strain, but by material fracture which can result in instantaneous catastrophic failures. Therefore, the application of high and low temperatures necessitates the consideration of fatigue and fracture mechanics.

3.3.1   Effects on Fatigue Crack Growth[16]

Figure 3-7 shows fatigue-crack growth characteristics as a function of environmental temperature. In this diagram, the stress range and

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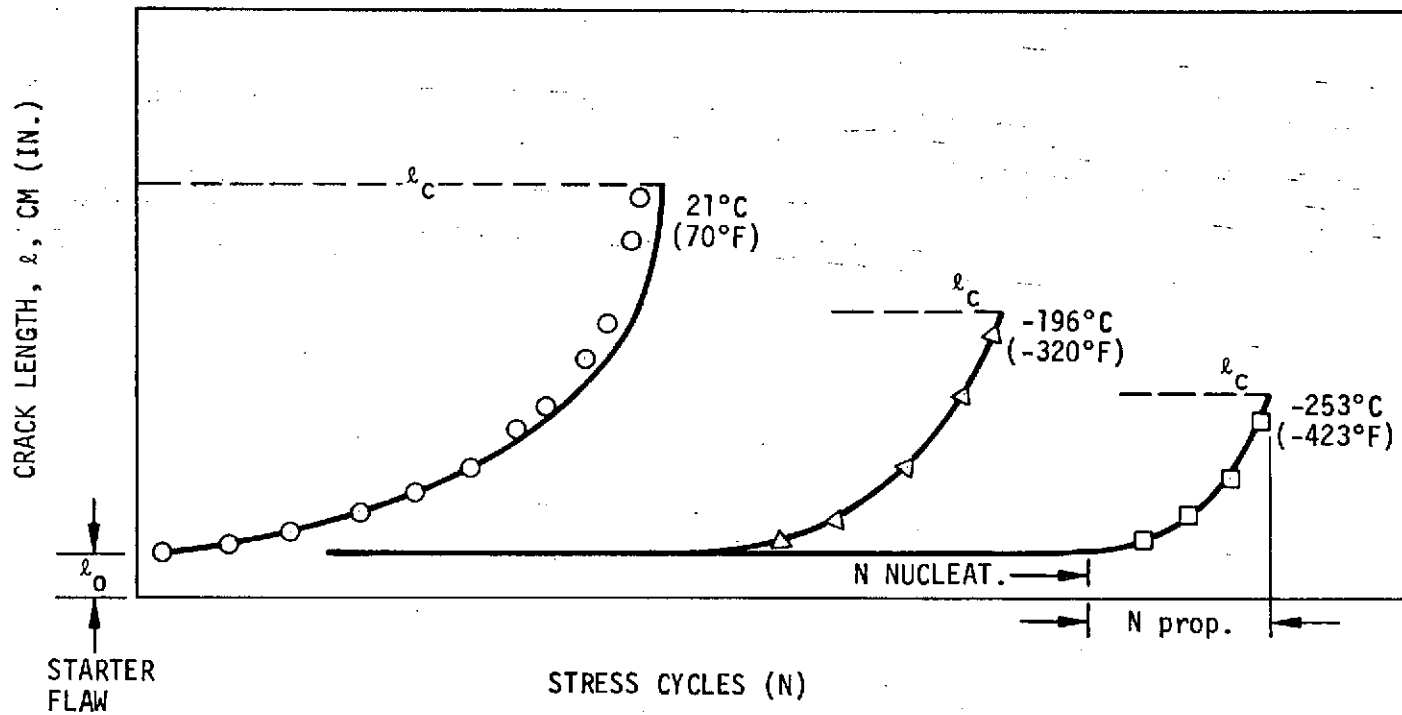
FIGURE 3-7: GROWTH OF FATIGUE CRACKS AS A FUNCTION OF
TEMPERATURE (SCHEMATIC) (REF. 16)

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3.3.1   (Continued):

stress level producing cracking are the same for all test temperatures
noted.   Several distinctive characteristics are evident in this figure.   The
diagram shows that the fatigue life increases as the temperature decreases.
It also illustrates a reduction in the critical flaw size or crack length that
can be tolerated as the temperature of a metal decreases.   It also indica-
tes that as the temperature <u>decreases</u> the crack nucleation period of time
to produce an observable crack <u>increases</u>.   Conversely, as temperature
<u>decreases</u>, the period of observable fatigue crack growth <u>decreases</u>.

3.3.2   Effects on Fatigue Life[16]

Figures 3-8 and 3-9 show fatigue test results as dependent on test tempera-
ture.   In these illustrations the total number of cycles-to-rupture as a
function of the various test stress levels are shown.   The total life in-
cludes the combined crack nucleation period and the fatigue-crack
propagation period.

3.3.3   Effect of Frequency at Elevated Temperatures[16]

The rate of fatigue-crack propagation as affected by rate of cyclic loading
and test-load frequency is an additional parameter to be considered.
In elevated-temperature fatigue testing, it is known that the number of
cycles to fracture decreases, and the crack-growth rate increases as
the speed or frequency of cyclic loads is decreased (Figure 3-10).   The
damaging, thermally activated mechanism of creep or creep cracking,
acting conjointly with fatigue, is responsible for this behavior.   In
general, this is true because, in the accumulation of stress cycles,
slower rates of load cycling result in exposure of the metal to tempera-
ture for longer periods of time than in high-speed tests.

3.3.4   Effect of Repeated Application of Heat on Fatigue Life[6]

Figure 3-11 shows the variation in the ratio of life with heat exposure
to life cold with temperature during heat exposure and the creep stress.
The results on which these trends are based were mainly obtained from
tests in which periods of heat, with or without mean stress application,
were applied periodically during the fatigue life; the mechanical loading
patterns included a sample representation of the gust loading and the
ground-air-ground cycles.   The trends, for aluminum alloy, give a
qualitative indication of behaviour, with the following conclusions:

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STRESS

-253°C
(-423°F)

-196°C
(-320°F)

24°C
(75°F)

316°C
(600°F)

N, CYCLES TO FRACTURE
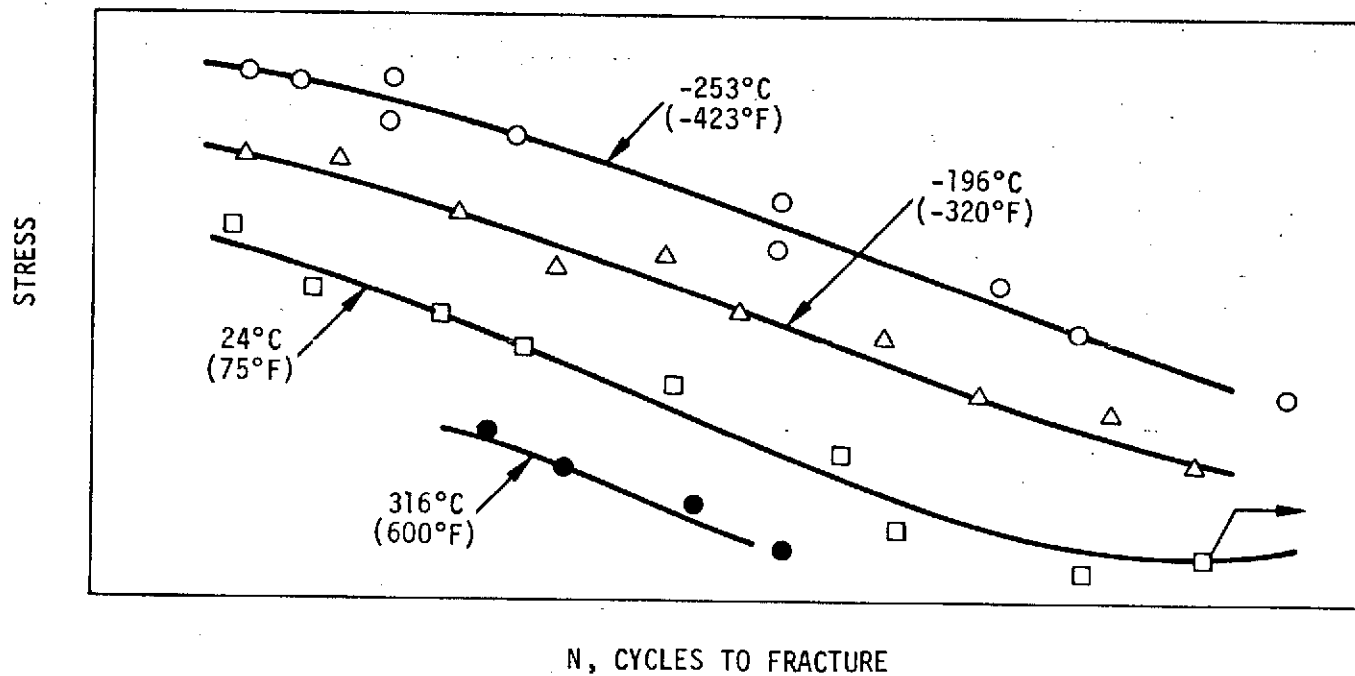
FIGURE 3-8: FATIGUE LIFE AS A FUNCTION OF TEST TEMPERATURE
(TYPICAL FOR MOST METALS) (REF. 16)

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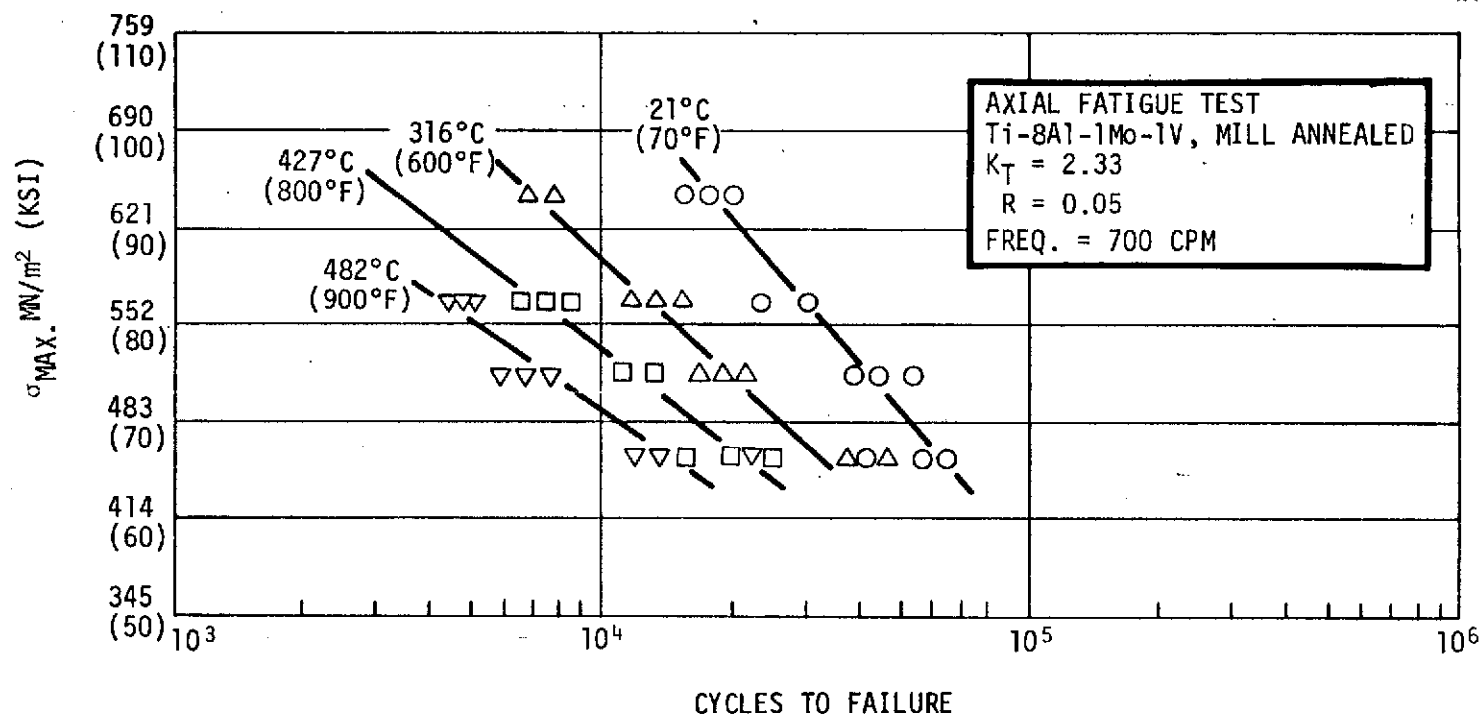
FIGURE 3-9: EFFECT OF TEMPERATURE (REF. 16)

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TEMPERATURE °C (°F)

649
(1,200)

427
(800)

204
(400)

0

700 CPM

40 CPM

20 MIN.
EXPOSURE

200 MIN.

AXIAL FATIGUE TEST

Ti-8Al-1Mo-1V, MILL ANNEALED
K_T = 2.33

σ_{MAX} = 569 MN/m^2(82.4 KSI)
σ_{MIN} = 28 MN/m^2 (4.1 KSI)

10^3 10^4 10^5 10^6

CYCLES TO FAILURE
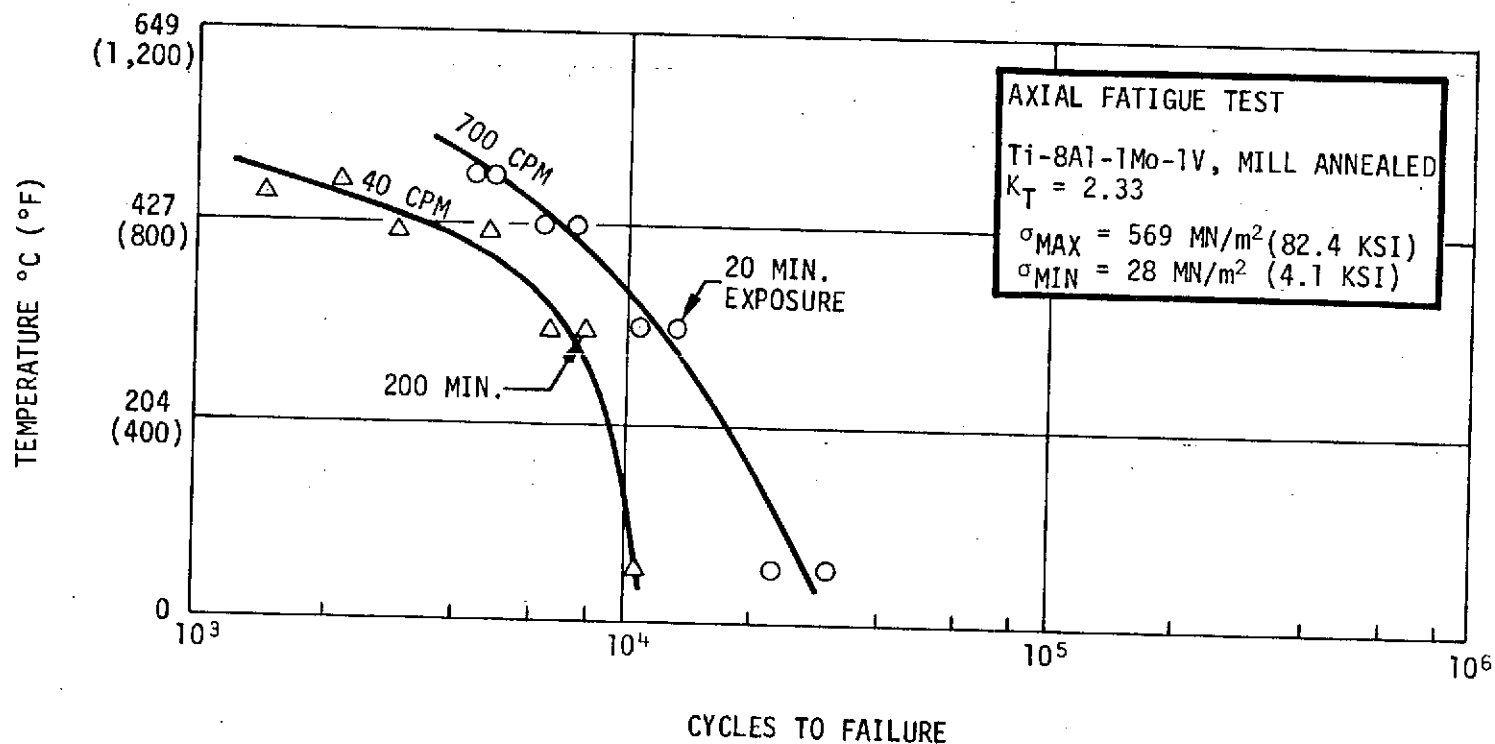
FIGURE 3-10:   EFFECT OF FREQUENCY AT ELEVATED TEMPERATURE (REF. 16)

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σ = CREEP STRESS, MN/m² (KSI)

NOTCHED SPECIMENS ————

100 mm
(3.9 in)

RIVETED JOINTS ————

100 mm
(3.9 in)

FABRICATED BOXES WITH ————
CENTRE JOINT

1m
(39.3 in)

$\dfrac{\text{LIFE WITH HEAT EXPOSURE}}{\text{LIFE COLD}}$

1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0

σ = 75 (11)

σ = 70→90 (10)→(13)

σ = 100 (15)

σ = 90→120 (10)→(20)

σ = 0

σ = 0

120   130   140   150   160   170   180
(248) (266) (284) (302) (320) (338) (356)

MAXIMUM TEMPERATURE, °C (°F)
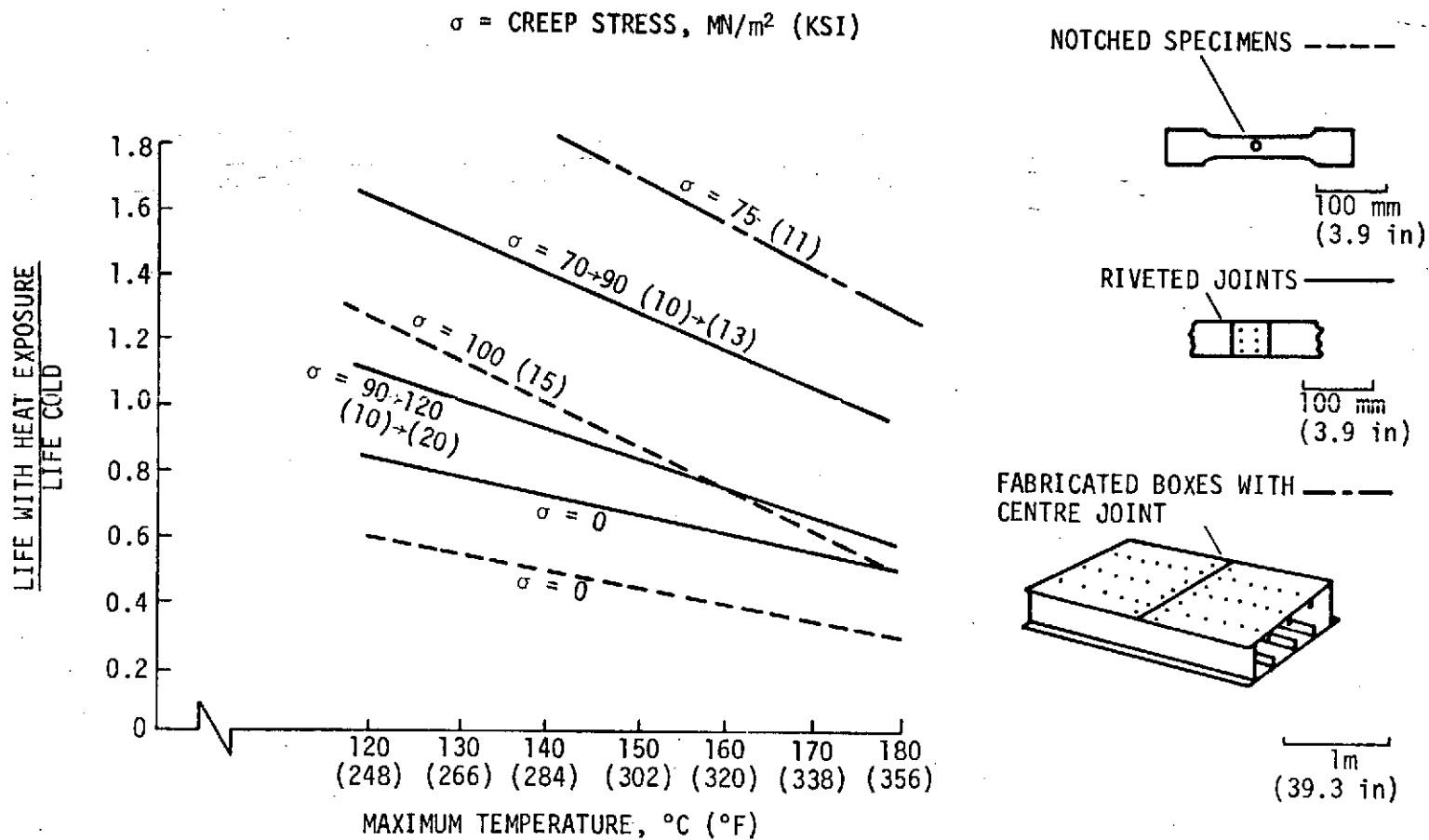
FIGURE 3-11: GENERAL TRENDS OF INFLUENCE OF TEMPERATURE AND MEAN STRESS
ON LIFE WITH INTERMITTENT HEATING (REF. 6)

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3.3.4   (Continued)

(1)   Performance reduces as the temperature rises from 120°
to 180°C (248° to 356°F).

(2)   Performance is better with tensile creep stress than with
zero creep stress, though the improvement is seen to be
falling off for the riveted joints at the higher creep
stresses.

(3)   Performance appears to improve in moving from the simple
notched specimen to the riveted-joint specimen and, again,
to the relatively complex fabricated box; reasons why this
may be so are discussed subsequently.

3.3.5   <u>Effect of Heat on Nucleation and Crack-Propagation Phases
of Fatigue Life</u>[6]

Figure 3-12 shows the effects of heat on the growth of fatigue damage at
different stages in the life of a specimen under test.   In all the tests,
fatigue cycling was carried out at room temperature under fluctuating
tensile loading.   After a mean (nominal) life to failure was established,
a single application of heat was introduced at a certain percentage of
nominal life; the fatigue cycling was stopped during this period, and the
mean load was adjusted to give tensile, zero, or compressive creep.
After cooling, the fatigue cycling was then resumed, and from considera-
tion of the total fatigue life to failure, the damaging or beneficial effect
of the heat exposure was assessed.   In the majority of the tests, the
heat exposure was 150°C (302°F) for 1000 hours, but the work also included
a small number of long-term tests in which the exposure was 120°C (248°F)
for 20,000 hours.   It is evident from the results of the tests on the notched
specimen that

(1)   Exposure to heat without load during the first half of the
fatigue life has a detrimental effect on fatigue performance.

(2)   This detrimental effect is to some extent alleviated by
tensile creep, and conversely.

(3)   Compressive creep increases the damaging effect of
heat alone.

(4)   Exposure to heat during the crack-propagation phase has
a relatively small effect.

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LOAD/TEMPERATURE ENVIRONMENT

NOTCHED SPECIMEN, Kt = 3.4

PINNED-LUG SPECIMEN, Kt = 3.1
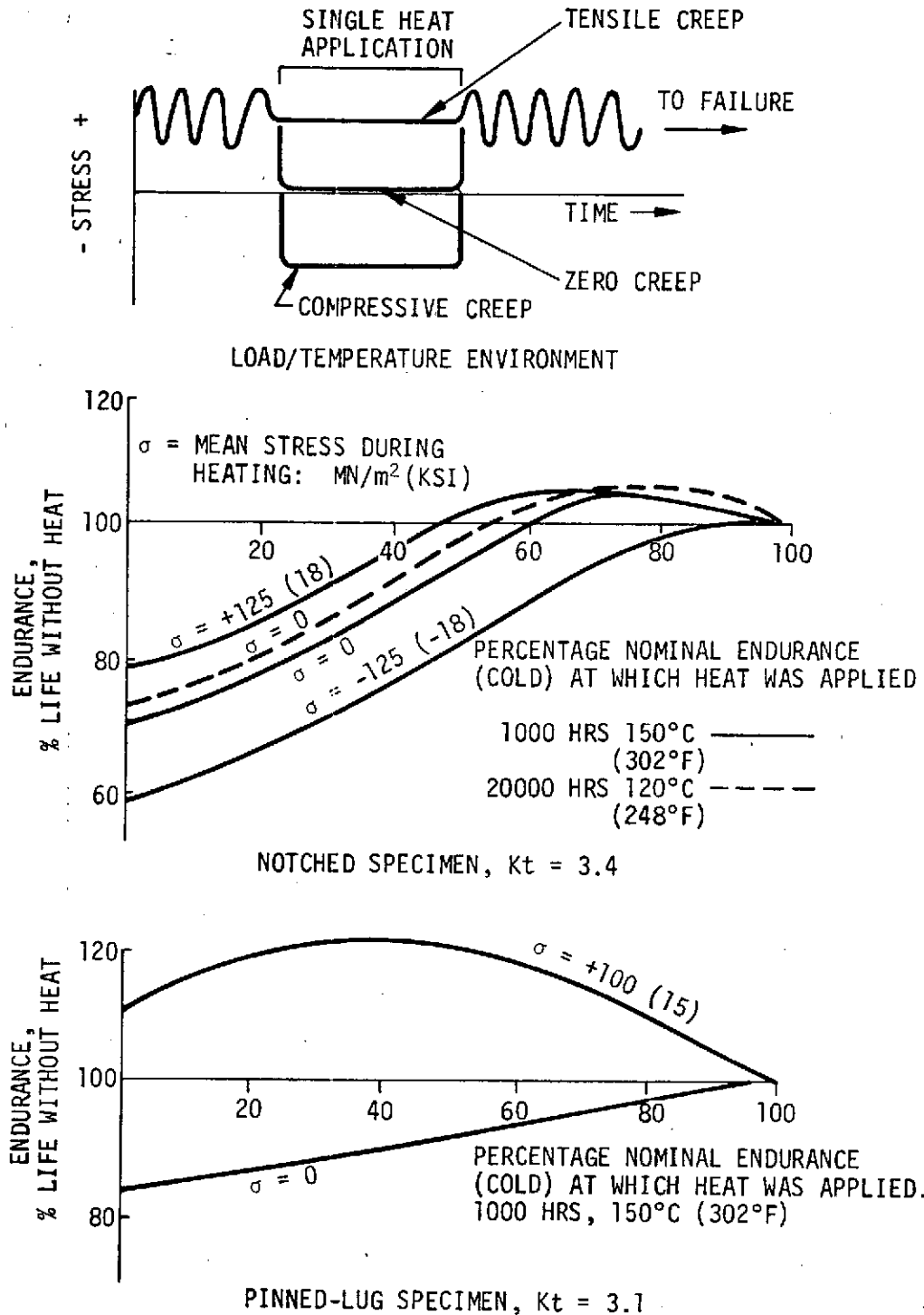
FIGURE 3-12: EFFECT OF HEAT EXPOSURE ON FATIGUE.
Kt IS STRESS-CONCENTRATION FACTOR.
(REF. 6)

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3.3.5   (Continued)

The foregoing test results, supported by examination of the fracture
surfaces, have led to a general explanation of the effects of heat and
creep on the growth of fatigue damage.   The effect of heat alone is to
speed up the development of fatigue damage nuclei and hence to reduce
the crack-initiation period; a marked reduction in scatter in endurance
has been noted after heat exposure, which is in keeping with this
explanation.   Until comparatively recently, the more rapid appearance
of damage nuclei was explained in terms of the relaxing effect of the
period of heat on beneficial residual compressive stresses which are
often inadvertently introduced at the notch surfaces during manufacture.
Recent metallurgical studies have shown that another, and perhaps more
important, change takes place in the surface material at the notch
during heating.

It has been found that machining leaves behind a work-affected zone some
50μ m (.002 in.) deep having a hardness approximately twice that of the
interior material.   In "as received" specimens, fatigue cracks, in fact,
initiated below this zone.   The heat exposure was found to reduce the
surface hardness to that of the interior material, and cracks then
developed from the surface.   This phenomenon, combined with some
relaxation of residual manufacturing stresses, is believed to explain
the observed reduction in crack-initiation time; the biggest reductions,
of course, were observed when heat preceded fatigue cycling.   When
load is applied during heating, plastic deformation of the material in the
vicinity of the notch will be encouraged; that is, tensile loading will
tend to induce compressive residual stresses at the notch so that after
the heating period, the local mean stress will be reduced with consequent
improvement in fatigue life relative to the heat-without-load condition.
The reverse will be true with compressive load with heating.

3.3.6   Concluding Remarks

1.   Fatigue life increases as the temperature decreases.

2.   Critical flaw size or crack length is reduced as the temperature
       decreases.

3.   Crack nucleation period, or time to produce an observable crack,
       increases as the temperature decreases.

4.   Conversely, as temperature decreases, the period of observable
       fatigue crack growth decreases.

3.3.6   (Continued)

5.   At <u>elevated temperature</u>, the number of cycles to fracture <u>decreases</u>, and the crack-growth rate <u>increases</u> as the speed or frequency of cyclic loads is <u>decreased</u>.

6.   Fatigue lives and crack-growth rates at cryogenic temperatures will be independent of frequency for most metals.

7.   At elevated temperature both deformation and fracture under fatigue or static loading are time dependent.

8.   The presence of <u>small</u> amounts of creep, as might be expected, tend to improve the fatigue life by reducing local stress concentration.

SECTION 4
TEST INTERACTIONS AND INCOMPATIBILITES

4.1 Ambient Temperature

4.1.1 Dynamic Tests and Static or Fatigue Tests

In reviewing structural-strength testing, it has been concluded that there are no significant incompatibilities between dynamic tests and static or fatigue tests. This conclusion has been reached after consideration of the following items:

(1) The stress levels in dynamic testing varies linearly with mode amplitude whose required magnitude in turn is regulated to a large extent by the response of the data acquisition system. Therefore, stress amplitudes can be made small enough so that they have no effect on the static strength capabilities or low-cycle fatigue life.

(2) The number of cycles applied in a dynamic test is very small compared to the total cyclic life of the specimen. The accumulated fatigue damage under low stress magnitudes and low number of cycles probably has negligible effects upon both low- and high-cycle fatigue life.

(3) Specimen alterations required in tests other than dynamic tests will probably have a negligible effect on mode shapes and frequencies; but in any case, they can be properly accounted for such that the results of the dynamic tests are not compromised.

4.1.2 Static and Fatigue Tests

4.1.2.1 Load Application System - Except for methods of load control, the load application systems used in static and fatigue tests are very similar. The following differences are noted:

(1) In static testing, loads are applied through tension pads; in fatigue testing, loads are applied through compression pads.

(2) Load distributions applied in static testing are more detailed than fatigue testing.

4.1.2.1 (Continued)

(3) Loading systems in static testing are designed for larger loads than in fatigue testing.

(4) Loading systems in fatigue tests are designed from fatigue point of view as opposed to strength as in static testing.

(5) Load control system in fatigue test is considerably more complex than that used in static test.

None of the differences in the load application systems are considered to be major incompatibilities between fatigue and static testing.

4.1.2.2 <u>Test Specimen</u> - The following differences in the test specimens between fatigue and static testing are noted:

(1) Application of high concentrated static loads requires local strengthening under tension pads or blocks. In the fatigue tests no local strengthening is permitted.

(2) In static tests, holes may be placed in structure as matter of expediency; in fatigue testing, holes are kept to a minimum.

None of the differences in the test specimen are considered to be major incompatibilities between fatigue and static testing. Incompatibilities can be resolved by limiting local configuration changes.

4.1.2.3 <u>Test Setup</u> - The following differences or similarities in the static and fatigue tests setup are noted:

(1) External configuration of loading fixtures are similar.

(2) Static test fixture is strength designed; fatigue test fixture is fatigue designed.

(3) Fatigue setup is designed to be quasi-permanent while a static setup is strictly temporary.

None of these differences are considered to be major incompatibilities between fatigue and static testing.

4.1.2.3   (Continued)

Static tests can be conducted in the fatigue-loading apparatus.   The reason for this is that the fatigue-test equipment has evolved into a very flexible, easy changeover system.   Magnetic tapes controlling hydraulic servo valves control the load distribution over the airframe.   Thus, changing to a different loading condition is no longer the time-consuming project of shifting jacks, repiping, and recheckout.   A new preprogrammed load-control magnetic tape is sufficient to accomplish the complete change to a new loading case

4.1.2.4   Testing Schedule - An almost universally accepted philosophy is that a structure must be qualified at least to design limit load before it is permitted to fly.   Since fatigue tests require a considerable amount of physical time due to safety factors, inspection, etc., this philosophy will probably require that a significant portion of static tests be performed prior to fatigue tests.   This constitutes a major incompatibility when considered with incompatibilities discussed below.

4.1.2.5   Material Reactions - If static tests are performed before or during fatigue tests, the high-cycle fatigue life will be increased as compared to the case if no static test were performed (this assumes that static tests are on the order of 80% of limit load or higher). This increase in fatigue life results from two effects:

(1)   Removing slack in mechanical joints, thereby reducing normally encountered stress concentrations.

(2)   Creating residual compressive stresses at crack tips, resulting in a decrease in crack propagation.

It is noted that static load which places residual tension stresses at the tip of a crack has an accelerating effect on crack growth.

If fatigue tests are performed prior to static tests, the probability of identifying all fatigue cracks prior to static testing is considered low. In normal fatigue testing a complete tear down of the structure is usually performed so that all fatigue cracks are identified and investigated.   Therefore, if fatigue tests are performed first, the possibility of a successful static test is somewhat remote, if indeed fatigue is a design consideration.

4.2   Elevated or Cryogenic Temperatures

4.2.1   Dynamic Tests and Static or Fatigue Tests

No detrimental elevated or cryogenic temperature effects will occur as the result of performing the dynamic test prior to either the static or fatigue tests, because the dynamic test is conducted at ambient temperature. Temperature effects are analytically resolved.

4.2.2   Static and Fatigue Tests

The effects of imposing elevated or cryogenic temperatures on a specimen which is destined to be consecutively subjected to either static/fatigue or fatigue/static test environments are as follows:

(1)   Continuously changing the imposed elevated temperature causes continuous changes in the material mechanical properties of the specimen. Therefore, it is not possible, for example, to use a single stress-strain curve.

(2)   Excessive localized strains can be induced by nonuniform temperature distribution.

(3)   Excessive localized strains can be induced by a uniform temperature imposed on complex geometrical configurations.

(4)   Elevated temperatures could have a detrimental effect on the fatigue life of a full scale vehicle specimen beyond that experienced in prior development testing. For full scale specimen, the relief of beneficial residual compression stresses and the decrease of material strain hardening caused by imposing elevated temperatures will accelerate the accumulation of fatigue damage.

(5)   Material creep is increased by elevated temperatures and can have a significant influence on fatigue life. Of the stresses induced by fatigue testing, it is the sustained or mean stress which is of primary concern in the evaluation of creep effects on specimen life.

(6)   Cryogenic or low temperatures increase material mechanical properties and as a result static strength and fatigue life are increased.

4.2.2 (Continued)

(7) Strain hardening of a material at low temperature is decreased, because of the increase in the material yield stress.

(8) Creep deformations of materials at low temperature are decreased.

(9) For a specific material, aging occurs at a reduced rate.

(10) Failure concerns at cryogenic temperatures are restricted to propellent tankage, which will be failure critical in the fracture mode when pressurized internally.

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SECTION 5

FEASIBILITY OF SINGLE TEST SPECIMEN (STS) CONCEPT

In previous sections of this report, we have discussed testing philosophies, interaction effects, compatibilities and incompatibilities of the three kinds of testing, namely; dynamic, static and fatigue testing. The purpose of this section is to evaluate the specimen damage resulting from performing the individual tests, their impact on scheduling and testing sequence. The results will then be used to select the most feasible testing sequence for which a criteria of testing will be presented in subsequent sections of this report.

5.1   Specimen Damage Resulting from Individual Tests

5.1.1   Dynamic Test

The test specimen will be undamaged at the completion of the dynamic test and the specimen will be suitable for subsequent testing (fatigue or static tests). These observations are based on the following:

(1)   The stress amplitudes can be held to a low level.

(2)   The number of cycles applied in dynamic testing are small.

(3)   As a result of (2) above, the accumulated fatigue damage are insignificant.

(4)   The test is conducted at ambient temperature; therefore, thermal stress will not affect the structure.

5.1.2   Static Test

Research evidence indicates that specimen failures during static tests can be expected to occur at loads $\leq$ limit in 1-of-10 tests conducted. Also, if loads are greater than limit but less than ultimate, specimen failures can be expected at less than ultimate in 5-of-10 tests. Figure 2-1 represents static test specimen failures of various structural components.

It can, therefore, be concluded that catastrophic failures, using the single test specimen concept, would eliminate the specimen for subsequent testing. Thereby, an additional specimen would be required to

5.1.2   (Continued)

complete the test program.   This action would nullify the single specimen
concept cost saving intent, and induce program scheduling delays.

Note: The above observations would also be applicable to the current
        two test specimen concept presently used in the aerospace industry.

5.1.3   Fatigue Test

The test specimen will be essentially undamaged at the completion of the
fatigue test and will be suitable for subsequent testing.   These observa-
tions are based on the following:

(1)   The test loads will be less than the design limit loads.

(2)   General yielding of the structure will not occur under
       limit loads.

(3)   Component testing during initial design provide fatigue-
       resistant structure which establishes an optimum quality
       design.

(4)   Thorough inspection procedures and repair are performed
       during and after fatigue testing.

5.2   Testing Sequence

In this paragraph, structural testing sequences are reviewed with the
intent of selecting the single test specimen (STS) most feasible testing
sequence.   The criteria for the recommended sequence will be pre-
sented in Section 6.0 of this report.

5.2.1   Dynamic, Static, and Fatigue

FIGURE 5-1:   TESTING SEQUENCE; DYNAMIC, STATIC, FATIGUE

5.2.1 (Continued)

A dynamic test followed by a complete static and fatigue test, Figure 5-1, is not technically feasible, because

(1) The weight critically of most major aerospace structures means that desigr. margins of safety approach → 0, and catastrophic failures of the static test article are expected when approaching ultimate load.

(2) Previously discussed data, show that the fatigue life is significantly improved by the application of high static stress.

(3) Static test article failure, which is likely near ultimate load, would eliminate the specimen for use in the subsequent fatigue test.

5.2.2 Dynamic, Fatigue, and Static

FIGURE 5-2: TESTING SEQUENCE; DYNAMIC, FATIGUE, STATIC

A dynamic test followed by a complete fatigue and static test, Figure 5-2, is technically feasible, because

(1) The performance of the dynamic and fatigue tests should not prohibit the successful completion of the static test. However, cracks not detected after completion of the fatigue test can cause premature failure during the static tests. Causes of premature failure can be determined by inspection.

(2) The specimen will not be destroyed at the completion of the dynamic and the fatigue tests.

5.2.3   Dynamic, and Combined Fatigue/Static Test

FIGURE 5-3:   TESTING SEQUENCE; DYNAMIC, COMBINED FATIGUE/STATIC

A dynamic test followed by a combined fatigue/static test, Figure 5-3,
is technically feasible because

    (1)   The application of design limit loads can be programmed
        into the fatigue test load sepctrum -- hence, no inter-
        ruption in fatigue testing is necessary.

    (2)   The probability of failure of limit static load is low.

    (3)   The specimen will not be destroyed at the completion of
        the dynamic and fatigue tests.

Note: The introduction of limit loads into the fatigue load spectrum will
      result in unrealistic fatigue life, if such loads do not occur in
      service. The effects must be determined by development tests
      of structural components.

5.2.4   Fatigue/Limit Static, Dynamic, and Ultimate Static

FIGURE 5-4:   TESTING SEQUENCE; FATIGUE/LIMIT STATIC, DYNAMIC,
               AND ULTIMATE STATIC

A combined fatigue/limit static test followed by a dynamic and an
ultimate static test, Figure 5-4, is technically feasible, because

    (1)   The application of design limit loads can be programmed
        into the fatigue test load spectrum -- hence, no inter-
        ruption in fatigue testing is necessary.

5.2.4   (Continued)

    (2)   The probability of failure at limit static loads is low, especially if this limit load is applied early in the program.

    (3)   The specimen will not be destroyed at the completion of the fatigue/limit static and dynamic tests.

Note: The introduction of limit static loads into the fatigue test spectrum will result in an unrealistic fatigue life, if such loads do not occur in service.   Therefore, high static loads may be applied after the aircraft life has been completed once.

5.3   Impact of STS Approach on Testing Schedule

In the current two specimen test concept, used by many aerospace companies, the fatigue tests are often scheduled after completion of the major portion of the static test program in order that a completely representative airframe, incorporating any required structural changes, be employed. And the requirement is that only one life time of fatigue testing must be completed prior to certification and continued to stay ahead of the aircraft in service.   The feasibility of this approach can be easily recognized especially when the service life and fatigue safety factor are high.

The results presented in this report seem to indicate the following important observations:

    (1)   The single test specimen (STS) approach will result in longer testing schedules than the current two specimen concept presently used.   This can be significant for high-cycle fatigue.

    (2)   For low-cycle fatigue testing, the impact of the STS approach on testing schedules is less significant.

5.4   Recommended Testing Sequence

The study to date indicates that a static test after a fatigue test is acceptable.   Therefore, the most feasible and recommended testing sequence, using the single test specimen concept, is a dynamic test followed by fatigue and static tests.   A static test to near design ultimate will provide sufficient proof that the structural design and stress analysis is sound and that the design allowables are valid.

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SECTION 6

SINGLE TEST SPECIMEN CRITERIA

In this part of the report, structural test criteria efforts are directed toward developments of requirements necessary for the structural testing of aerospace hardware using a single test specimen (STS) for dynamic, fatigue and static testing. The development will include: 1) required changes in design techniques, 2) changes in analysis techniques, and 3) establishment of test criteria including test sequence. These requirements are intended to ensure adequate strength and service life for the flight vehicle in the performance of its mission.

In formulating the criteria, the merits of the different types of tests, the difficulties associated with simulating thermal effects and cost, which is the primary driver in proposing the single test article concept, have been carefully considered.

6.1   Testing Sequence

Using the single test specimen (STS) concept, the following testing sequence is recommended:

      a. Dynamic test;
      b. Inspect and re-instrument;
      c. Fatigue test to required number of lifetimes;
      d. Inspect and re-instrument;
      e. Nondestructive static test (to limit load);
      f. Inspect

6.2   Structural Development

It has been recommended that the fatigue test be conducted after the dynamic test but prior to the static limit test. Successful completion of the static test, is therefore, dependent on the crack propagation and fatigue properties of the selected structural material. Therefore, selection of the structural material must be based on the following:

      (1)   Strength/weight ratio at pertinent temperatures

      (2)   Fatigue properties and metallurgical stability

      (3)   Resistance to corrosion and stress corrosion when applicable

6.2   (Continued)

   (4)   Fabrication properties

   (5)   For supersonic flights, lower product of the modulus of
          elasticity and the coefficient of thermal expansion (E).
          This produces smaller thermal stresses for a given
          environment.

Consideration must also be given to deterioration of material properties,
creep and fatigue characteristics of the material at elevated temperatures.

If the material is subjected to long periods at elevated temperature while
under load, it is necessary to ensure that the amount of creep occurring
is limited so that unacceptable deformation of the structure is prevented.
An upper limit of 0.1% total plastic strain is often chosen as a reasonable
criterion (Reference 6).

6.3   Research and Development Tests

The single test specimen concept requires that a comprehensive and
effective research and development test ranging from small specimens
through full scale components be performed, so that the interactions
of the various parameters are understood and properly accounted for.
The extent of these tests are dependent on the type of mission.

The smaller specimens must be used primarily for screening materials,
processes, methods of fastening, and where applicable, temperature
effects.

In supersonic flights, to see whether creep, overageing, repeated
application of thermal cycles, fatigue from externally applied load and
fatigue from thermal stress cycles interact with each other, a vast
number of tests to compare fatigue lives must be done under various
combinations of conditions. The aim of this work is to provide design
data and serve as a guide to the planning and interpretation of the major
tests.

Large component specimen testing must also be performed. Actual
components of the aircraft or flight vehicles such as parts of the wing
and fuselage must be tested to assist in design development. Together,
these specimens may almost make a complete airframe. The wide
range of tests should include, when applicable, exploration of tempera-
ture and stress distributions under various conditions, effects of real
time temperature on fatigue life, static tests to demonstrate the strength

6.3   (Continued)

of the structure under extreme conditions and fatigue tests to show its behavior under recurring loads in service.

These test specimens are normally fabricated to early prototype standards or pre-production standards.

Summarizing then, the use of the single test specimen concept for dynamic, fatigue and static testing, requires that an effective program of development testing be performed.

6.4   Certification Tests

Certification of the aerospace structures will probably be based partly on calculation, but most emphasis will continue to be placed on the major acceptance tests. Thus the dynamic, fatigue and static tests must be done on the whole airframe.

6.4.1   Test Specimen

The requirement is that the test article must be structurally complete and properly represent the aerospace vehicle to be proved. In other words, the test article must be fabricated to production drawings with the same materials, processes, methods and tools used in manufacturing the flight hardware.

Because of schedule limitations, the test article should be the first production article fabricated.

When components of structure must be used to qualify full-scale structures, the test article should include sufficiently representative supporting hardware and adjacent materials to permit proper boundary conditions.

6.4.2   Test Conditions

Because of the diverse nature of aerospace vehicle structural configurations and differing mission requirements, it is impractical to recommend a universal test condition. The minimum conditions selected, however, should, if practical, include the combination of loads and environments that dictated the design of the article to be tested.

6.4.2   (Continued)

Each test condition must be carefully selected from the usually large number of design conditions. The test loads must be chosen so that the damaging fatigue loading actions likely to occur in service are properly represented.

The assessment of what loads need to be applied is extremely complex. Considerations must be given as to what is practical from the testing standpoint. For example, if a relatively small component of a major structure is the only critical part for total vehicle design conditions, this component may be tested at a lower level of assembly.

6.4.3   Dynamic Test

The purpose of the dynamic test, frequently referred to as GVT (Ground Vibration Test), is the determination of the natural modes of vibration of the basic structural components. Through reduction of the data obtained from such a test each natural mode is identified and described by the frequency, mode shapes and structural damping factors associated with it. With this dynamic description the validity of the mathematical model used in earlier theoretical analyses is substantiated.

The selected boundary conditions should consist of soft support points, wherever possible, in an attempt to simulate a free structure so that free-body modes may be obtained. Rigid boundary conditions are sometimes used especially for large flexible structures where a soft support system is difficult to achieve.

The excitation of the test article should be provided by electro-magnetic or similar shaker units. The locations selected for the shakers should be governed by the component being tested. Normal excitation level is throughout a frequency range of 0 to 40 cps for airplane components and 0 to 100 cps for launch vehicle structures.

The stress levels in a GVT vary linearly with mode amplitude whose required magnitude in turn is regulated to a large extent by the response of the data acquisition system. Therefore, stress amplitudes should be small enough so that they effect neither the static nor the fatigue capability. The magnitude of these stresses should be well below the endurance limit of the material used.

The dynamic test should be performed at room temperature with thermal testing to be accomplished on separate components, if necessary. This

6.4.3 (Continued)

is desirable because electrical power requirements for simulation of heat loads can be astronomical when considering very large heated areas. Also, representation of temperature gradients and distribution cannot be adequately achieved. On Saturn V, thermal testing on components were performed separately (S-IC forward skirt, S-II thrust cone, etc.)

6.4.4 Fatigue Test

The purpose of the fatigue test is to subject the test specimen to the whole structural load environment anticipated in service with the objectives of:

(1) Locating the more fatigue-critical structural locations,

(2) Demonstrating satisfactory resistance to fatigue crack initiation and propagation,

(3) Providing data for maintenance and repair and to verify inspection techniques, and

(4) Obtaining an estimate of the service fatigue life.

This then, would require that the test specimen be taken through a series of flight sequences and subjected to the environmental conditions it would encounter in typical flights. These loading conditions must be applied to the specimen flight after flight to build up in the specimen all the fatigue structural experience which the flight vehicle will accumulate in service.

The questions that are often considered in planning and performing the fatigue test are numerous. Some of the significant questions are

(1) How to compress the test time.

(2) Should the test be conducted at room temperature (RT) or should design temperatures be simulated?

(3) Should real-time testing be compromised so the fatigue can be completed in an acceptable time?

To answer all these questions is no easy task. The final decision would definitely depend on cost, scheduling and feasibility of adequately estimating the service life of the flight hardware.

6.4.4   (Continued)

The most technically desirable way would be real-time, real-temperature approach, i. e. same time duration, and same temperature magnitudes and distributions, as for an actual flight. The duration of the test when the necessary allowances for downtime are made, would approach or exceed the useful life of the flight article. This type of test would be, for large service life requirements, unacceptable from a practical standpoint. Therefore, in order to complete the test within an acceptable time, and especially in supersonic flights with the thermal cycle, full scale fatigue tests always have been conducted to simplified conditions. This has been necessary for both technical and practical reasons. Accordingly, the limitations, difficulties, cost and feasibilities involved in fatigue testing have been carefully considered in developing the fatigue test criteria.

6.4.4.1   Load Application - To give the correct combination of spectrum loads, internal pressure and GAG (ground-air-ground cycle) etc., the test must be conducted on a flight-by-flight basis.

6.4.4.2   Preloads Effects - Application of high static loads during the fatigue test should be avoided. Previously discussed data, show that high-cycle fatigue life is significantly improved by the application of such loads. However, if it is necessary to include such loads, they may be applied in the fatigue test after the service life has been completed once.

6.4.4.3   Inspections - Complete fatigue test inspection must be performed, and detrimental cracks detected, to allow a subsequent successful static test.

Inspections must be scheduled such that the inspections will be more frequent in the later stages of the test programs. These inspections must be accomplished using dye penetrants, ultrasonic, etc. to locate and define fatigue damage. The time normally expected for inspection is approximately 35% of the total test program.

6.4.4.4   Real-Time Testing - Real time fatigue testing takes a long time, particularly where high fatigue safety factors are to be maintained. Therefore, real-time testing must be used only for short service lives (low cycles) or whenever their impact on scheduling can be tolerated. For instance, the 2,000 flights, safe life requirement of the Space Shuttle Orbiter (a factor of 4 on 500 flights) is relatively short when compared to the fail safe requirement of a typical airliner,

6.4.4.4   (Continued)

20, 000 flights (no factor), therefore, fatigue testing of the Space Shuttle in real-time is seen as an advantage because it is not necessary to compress the time/temperature history which often leads to questionable test conclusions.

6.4.4.5   Accelerating the Test - In the subsonic regime (no temperature effects) currently used test time compression methods must be used.   They are as follows:

(1)   By eliminating the time between the cycles, the loading actions are compressed so that a test cycle is considerable shorter than the flight it represented.

(2)   At times all load cycles below a given amplitude cycle are eliminated or a large number of low amplitude cycles are replaced with a smaller number of high amplitude cycles causing equal fatigue damage.

The effects of item (2) above on fatigue life have been discussed in Section 3.   If their effects on fatigue life can be shown to be insignificant by analysis and development testing, then using item (2) in addition to item (1) results in greater test time compression, which in the case of the single test specimen is desirable.

For supersonic operations, test time compression methods described in Reference 11 and briefly discussed in Section 2 are applicable.

6.4.5   Static Test

The purpose of the static test is to show that the structure is capable of withstanding extreme service conditions and to demonstrate margins of safety.

This large and comprehensive test must be performed after completion of the major-fatigue test because substantial data indicate that there would be a significant increase in high-cycle fatigue life.   There is also a high probability of catastrophic failure during static testing.

The static test must be completed before certification of the aircraft. All the important static testing conditions will have been covered and practical demonstration given in the test that the vehicle is capable of withstanding the critical design conditions.

6.4.5.1   Test Setup - The static test can be conducted in the fatigue loading apparatus. The reason for this is that the fatigue-test equipment has evolved into a very adaptable, easy changeover system. Magnetic tape controlled hydraulic servo valves control the load distribution over the airframe. Thus, changing to a different load condition is no longer the time consuming project of shifting jacks, repiping, and recheckout. A new preprogrammed load control magnetic tape is sufficient to accomplish the complete change to a new loading case.

6.4.5.2   Load Application - The test specimen must be subjected to a series of tests each conducted to limit load on a fully instrumented airframe. These tests shall simulate the loads resulting from all the critical flight and ground handling conditions, and the specimen must be able to withstand these loads with an adequate margin of safety.

In planning the test, the load should be built up in a series of steps in the usual way but full use of the computer should be made to examine strain and deflections at each step and to compare them with expected values. By this means it is possible to detect the onset of failure and to stop the test before catastrophic damage occurs.

6.4.5.3   Interpretation of Results - The measured strain gauge results from the test can be extrapolated to ultimate conditions and ability to carry ultimate load can be proven by comparison with previously tested structure. Where extensive component tests did not exist several ultimate tests can be made on structural components.

6.4.5.4   Temperature Simulation - The thermal environment anticipated in service must be simulated. The loadings must be grouped so that those without heating are done first.

Whenever moderate temperatures accompanied by small thermal stresses are expected, the static test can be conducted at room temperature (RT). Thermal effects can be accounted for by using additional factors on the applied loads. These applied load ratios are established by some rational procedure which allows for material property variation and the presence of temperature induced thermal stresses. Static development tests on large component specimens provide data for determining such factors.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

(1)   The contracted study indicates that the single test specimen (STS) approach for performing dynamic, fatigue and static testing on aerospace and aircraft structures is feasible.

In a wing carry through structure study for the Air Force (References 17 and 18), Boeing has already performed analyses and developed techniques which show that using a single hardware item for both static and fatigue tests is feasible. This study involved the design and analysis of a Wing Carry Through Structure for an Advanced Strategic Bomber.

Performing an additional dynamic test on the same test article would not compromise this feasibility because the stress amplitudes can be held to a low level (see Reference 2) and the number of cycles applied are small, which results in insignificant accumulated fatigue damage.

(2)   The recommended testing sequence, using the (STS) concept, is a dynamic test followed by a fatigue and static test.

In a recent Wing Carry Through Structure study (Reference 18), Boeing concluded that a static test to near design ultimate load would provide sufficient proof that the structural design and stress analysis were sound and that the design allowables are valid. In addition, based on statistical techniques and exceedance data used in B-52 C-F Model studies, the probability of the structural capability exceeding the design load as a function of static test load level was determined. These results, shown in Figure 7-1, indicate two things: first, that analytical methods used to predict design loads should possibly be modified to reflect more realistic probabilities of encounters; and secondly, that using existing load prediction techniques, static test to fractional levels of design loads can qualify structural assemblies to high reliabilities.

In major wing and fuselage static ultimate and destruction tests on the 737 airplane (Reference 19), components that failed during the test were subsequently reinforced and shown good for ultimate load by extrapolated test data.

(2) Continued -

In another test program (Reference 20), the Lunar Roving Vehicle (LRV) chassis was statically qualified by testing to limit loads with the exception of one design condition where ultimate test loads were used.

(3) If high static loads are applied during the fatigue test, date show that high-cycle fatigue life will be increased as compared to the case if no static loads are applied (Reference 12). This increase is due to the beneficial residual stresses developed at the tip of cracks.

(4) The STS concept requires that comprehensive and effective research and development tests ranging from small specimen through full-scale components be performed. This is necessary so that the interactions of the various parameters are understood and properly accounted for. In supersonic flights, additional development tests must be planned and performed to study the effects of the thermal cycle, test time compression, etc.

(5) The test article must be structurally complete and properly represent the aerospace vehicle to be proved.

(6) The dynamic test must be conducted at room temperature (RT). If applicable, thermal testing must be done separately on representative components. This approach was used on the Saturn V program (Reference 21), where thermal testing on components were performed separately (S-IC forward skirt, S-II thrust cone, etc.)

(7) It is recommended that real-time testing be performed whenever possible. This would be more appropriately applied to short service life. For long lives and high fatigue factors of safety, test time compression methods must be applied to keep the testing time acceptable.

(8) Complete fatigue test inspection must be performed, and detrimental cracks detected, to allow a subsequent successful static test.
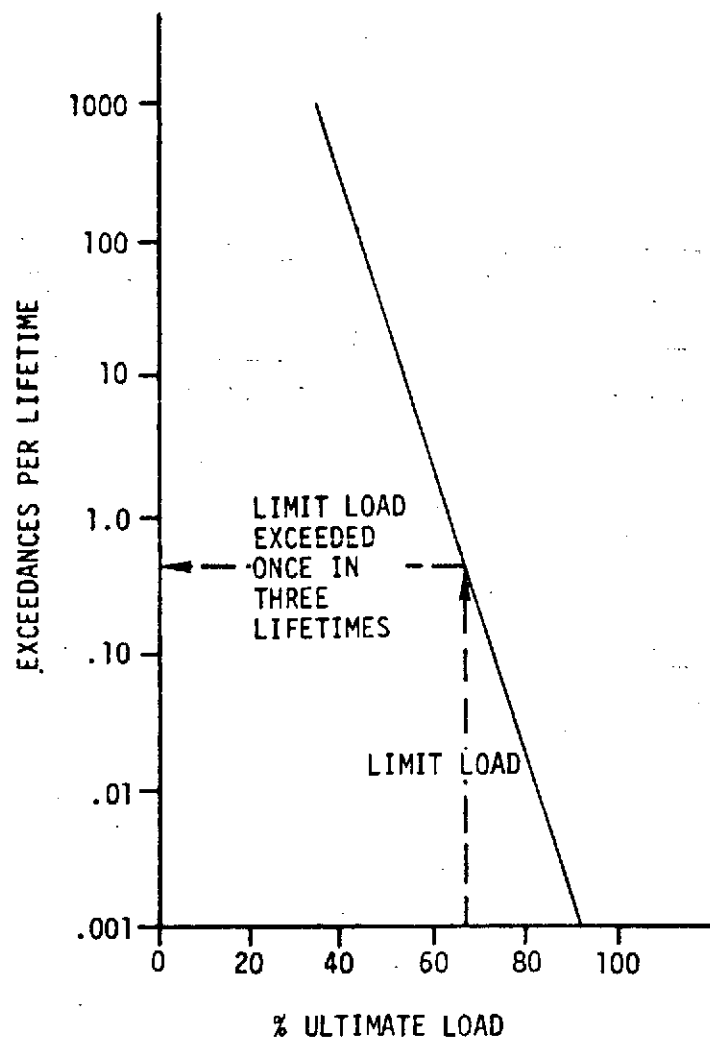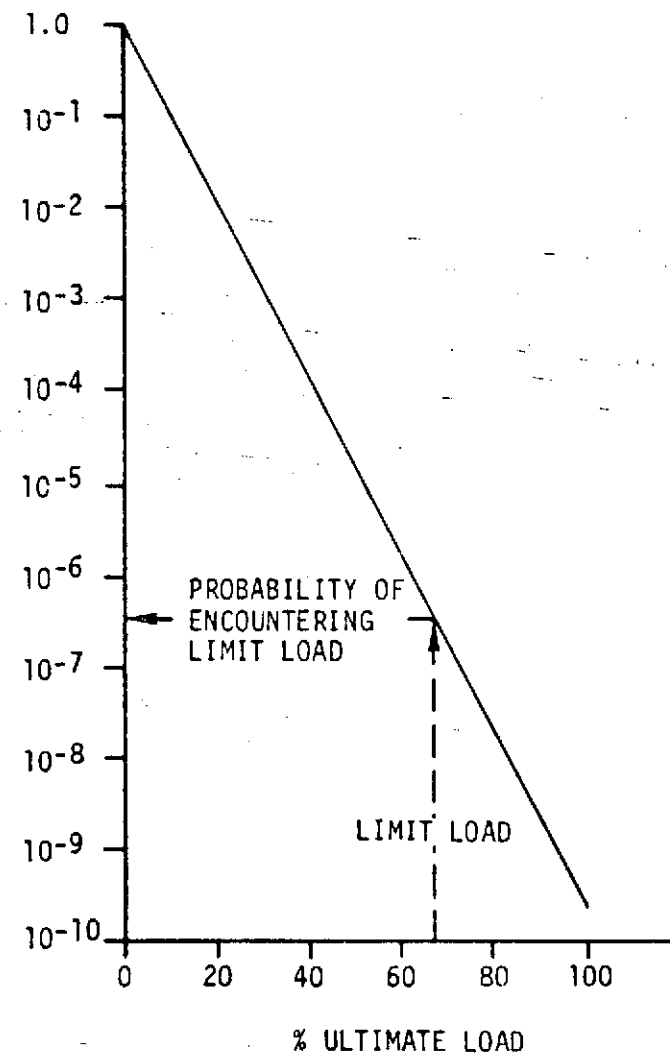
FIGURE 7-1: B-52 SERVICE LIFE DATA INDICATES FEASIBILITY OF TESTING
TO FRACTION OF DESIGN LOAD

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D6-9447 TN   Evaluation of Vibration Methods to Separate Closely
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T6-2109   Ground Vibration Test of the Model 727 Airplane

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               Assembly

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D5-11938   Component Structural Development Test Program

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APPENDIX

APPLICATION OF STS CONCEPT TO SPACE SHUTTLE ORBITER

The charts provided in this Appendix illustrate the application of the single test specimen (STS) concept to the Space Shuttle Orbiter structural testing.

The objectives of these charts are to address the Space Shuttle Orbiter structural testing in regard to the following:

(1) Review current two test article concept and assess various sequence and combinations of Orbiter structural testing

(2) Assess using a single Orbiter test article to perform dynamic, static and fatigue testing.

Also shown is the impact on scheduling.

THIS PRESENTATION

● PRESENTATION OBJECTIVE

USING THE INFORMATION ALREADY GATHERED IN FULFILLING CONTRACT NAS8-29070, ADDRESS THE SPACE SHUTTLE ORBITER STRUCTURAL TESTING IN REGARD TO THE FOLLOWING:

   ● REVIEW CURRENT TWO TEST ARTICLE CONCEPT AND ASSESS VARIOUS SEQUENCE AND COMBINATIONS OF ORBITER STRUCTURAL TESTING

   ● ASSESS USING A SINGLE ORBITER TEST ARTICLE TO PERFORM GROUND VIBRATION, STATIC, AND FATIGUE TESTING.

● WHY ADDRESS THE ORBITER?

   ● IT IS AN OPPORTUNITY TO APPLY TO A SPECIFIC VEHICLE, WHICH HAS A DEFINED MISSION AND AN EXISTING DESIGN, THE PRINCIPLES ALREADY DISCLOSED FROM CONTRACT WORK.

   ● IF COST SAVINGS IN THE ORBITER STRUCTURAL TEST PROGRAM ARE TO BE REALIZED,   ACTIONS MUST BE INITIATED NOW FOR THEM TO BE ACHIEVED.

GROUND RULES FOR ORBITER ASSESSMENT

● ALL BASIC TEST OBJECTIVES MUST BE ATTAINED

● COMPLIANCE WITH CURRENTLY DEFINED TEST PROGRAM CRITERION MUST
BE MAINTAINED

● MINIMIZE CURRENT SCHEDULE IMPACT

GROUND RULE - BASIC TEST OBJECTIVES

- **GROUND VIBRATION TEST (GVT)***

  - VERIFY VEHICLE STRUCTURAL DYNAMICS

  - MEASURE DAMPING CHARACTERISTICS

- **STATIC TEST**

  - DEMONSTRATE VEHICLE STRUCTURAL INTEGRITY FOR DESIGN LIMIT LOADS
    IMPOSED UNDER THEIR APPLICABLE ENVIRONMENTS.

  - DEMONSTRATE VEHICLE STRUCTURAL CAPABILITY TO SUSTAIN DESIGN ULTIMATE
    LOADS IMPOSED UNDER THEIR APPLICABLE ENVIRONMENT.

- **FATIGUE**

  - VERIFY THAT THE FATIGUE LIFE OF THE VEHICLE IS $\geq$ DESIGN SERVICE LIFE
    (2,000 MISSIONS).

  - REVEAL WEAKNESS AND ENABLE CORRECTIVE ACTION TO BE TAKEN BEFORE THE
    SAME PROBLEM OCCURS IN OPERATION

*ACOUSTIC DYNAMICS IS NOT CONSIDERED

GROUND RULES - TEST PROGRAM CRITERION COMPLIANCE

- **GVT**

    - WILL BE AN INTEGRATED ASSEMBLY TEST IN WHICH THE ORBITER IS TESTED SEPARATELY AND TOGETHER WITH THE EXTERNAL TANK (ET) AND SOLID ROCKET BOOSTERS (SRB).

    - GVT MUST BE COMPLETED BEFORE FMOF (FIRST MAN ORBITAL FLIGHT).

- **STATIC TEST**

    - TESTING FOR CRITICAL DESIGN MANEUVERING AND LANDING LIMIT LOADS MUST BE COMPLETED BEFORE FIRST HORIZONTAL FLIGHT (FHF) TEST IS INITIATED.

    - TESTING FOR CRITICAL DESIGN MANEUVERING AND LANDING ULTIMATE LOADS MUST BE COMPLETED BEFORE 80% OF DESIGN LIMIT LOADS CAN BE EXCEEDED DURING FHF.

- **FATIGUE TEST**

    - THE ACCUMULATED TEST TIME MUST EXCEED OPERATIONAL TIME BY THE SERVICE LIFE TIMES THE DESIGN FATIGUE SCATTER FACTOR.

GROUND RULES - CURRENT SCHEDULE

● CURRENT TWO-TEST ARTICLE PROGRAM SCHEDULE

TESTS \ ARTICLE AVAILABILITY	1972				1973				1974				1975				1976				1977				1978				1979				1980			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4

ATP (▽), FHF (▽), FMOF (▽)

STA △ · ET FTA △△ · SRB △

FATIGUE — II

GVT — I

STATIC (LIMIT/ULTIMATE) — SPECIMEN I
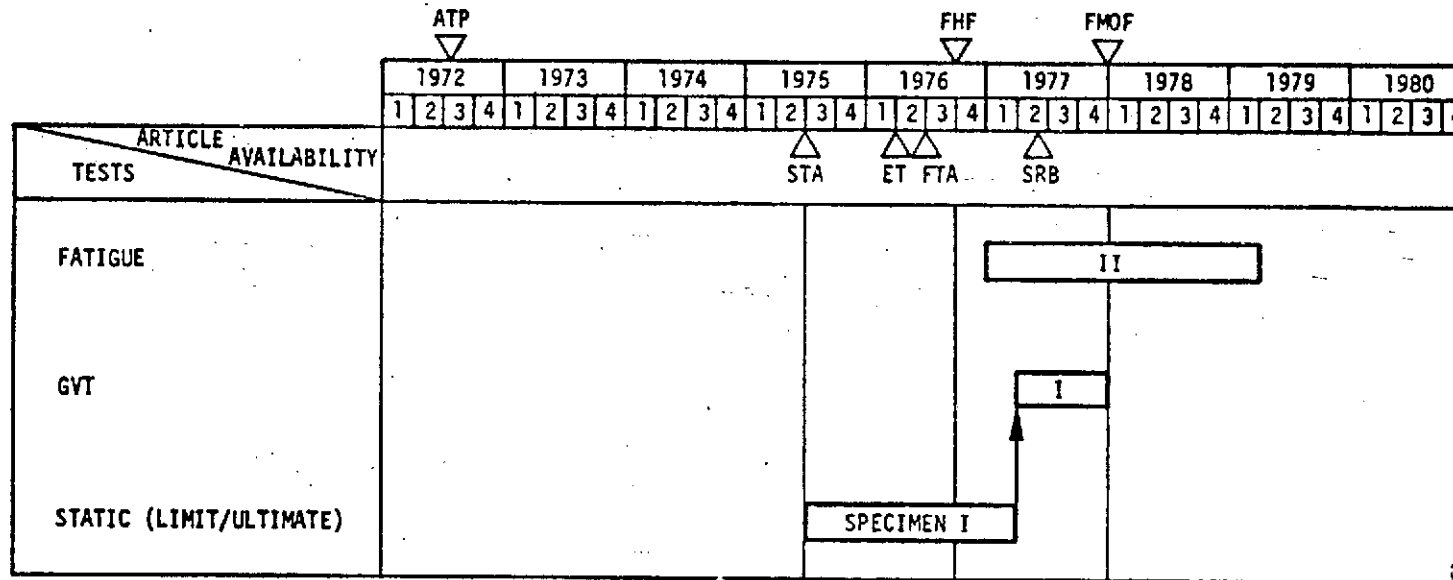
NOTE: ALL TIMES INCLUDE TEST SETUP AND PERFORMANCE; REF. NR.

● PROGRAM

   ● CRITICAL DESIGN LIMIT STATIC TESTS ARE CONDUCTED BEFORE FHF AND ULTIMATE STATIC
     TESTS ARE PERFORMED DURING FHF, BUT MUST BE COMPLETED BEFORE FMOF

   ● GVT MUST BE COMPLETED BEFORE FMOF, BUT NOT BEFORE FHF

   ● APPROXIMATELY A YEAR OF FATIGUE TESTING OCCURS BEFORE FMOF, BUT NO FATIGUE TESTING
     IS PERFORMED BEFORE FHF

   ● AVAILABILITY OF THE EXTERNAL TANK (ET) AND SOLID ROCKET BOOSTERS (SRB) DICTATE THE
     PERFORMANCE SCHEDULE OF THE INTEGRATED GVT

ADDITIONAL ORBITER STRUCTURAL TEST CONSIDERATIONS

NOW THAT THE PRESENTATION OBJECTIVE HAS BEEN DEFINED AND THE GROUND RULES FOR ASSESSING THE ORBITER STRUCTURAL TESTING STIPULATED, LET US NOW CONSIDER THE FOLLOWING:

- STATIC AND FATIGUE TEST INFORMATION DESIRED IN ADDITION TO THE BASIC TEST OBJECTIVES

- ORBITER STRUCTURAL TEST CHARACTERISTICS

- APPROACH TO UNDERSTANDING THE ORBITER TESTING THERMOMECHANICAL EFFECTS

- SPECIMEN DAMAGE RESULTING FROM PERFORMING INDIVIDUAL TESTS

    - GVT

    - STATIC TEST

    - FATIGUE TEST

ADDITIONAL TEST INFORMATION DESIRED

● STATIC TEST

- DATA TO VERIFY STRESS ANALYSIS CONCLUSIONS

- IDENTIFICATION OF DESIGN DEFICIENCIES

- STRUCTURAL INFLUENCE COEFFICIENTS

- DATA TO ESTABLISH GROWTH POTENTIAL

● FATIGUE TEST

- DATA TO VERIFY DESIGN FATIGUE ANALYSES

- DATA TO VERIFY SERVICE INSPECTION CRITERIA, TECHNIQUES, AND REQUIREMENTS CONSIDERING TURNAROUND OPERATIONS.

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CURRENT ORBITER STRUCTURAL TEST CHARACTERISTICS

- **GVT**

  - PLANNED TO BE PERFORMED ON A SPECIFICALLY ASSIGNED TEST SPECIMEN.

  - PLANNED TO BE TESTED IN VERTICAL POSITION.

  - PLANNED TO BE TESTED AT AMBIENT TEMPERATURE.

- **STATIC TEST**

  - A SIGNIFICANT VARIETY OF DIFFERENT TEST LOAD CONDITIONS WILL BE IMPOSED (LIFT-OFF, BOOST, RE-ENTRY, MANEUVERING, ETC.) WHICH WILL NECESSITATE DIFFERENT LOAD APPLICATION SETUPS.

  - SERVICE ENVIRONMENT THERMAL CONDITIONS WILL BE IMPOSED.

  - THE ORBITER THERMAL PROTECTION SYSTEM (TPS) WILL NOT BE INSTALLED. THE BARE METAL OF THOSE COMPONENTS WHICH WILL BE PROTECTED IN SERVICE WILL BE EXPOSED RESULTING IN MORE EFFECTIVE USE OF TEST SITE HEAT SOURCES.

- **FATIGUE TEST**

  - POSSIBILITY OF REAL TIME FATIGUE TEST EXIST BECAUSE OF THE SHORT DESIGN LIFE (2,000 MISSIONS) AND THE SHORT EXPOSURE TIME PER MISSION (1 HR/MAX) TO LOADS WHICH INDUCE FATIGUE DAMAGE.

  - THE SPECIMEN WILL NOT BE A WHOLE VEHICLE.

  - SERVICE ENVIRONMENT THERMAL CONDITIONS WILL BE IMPOSED.

  - TPC WILL NOT BE INSTALLED.

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TEST ARTICLE CONFIGURATIONS

STATIC STRENGTH

18'
27'
84'
91'
111'
26'
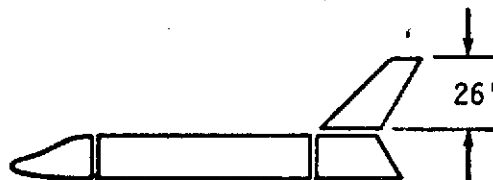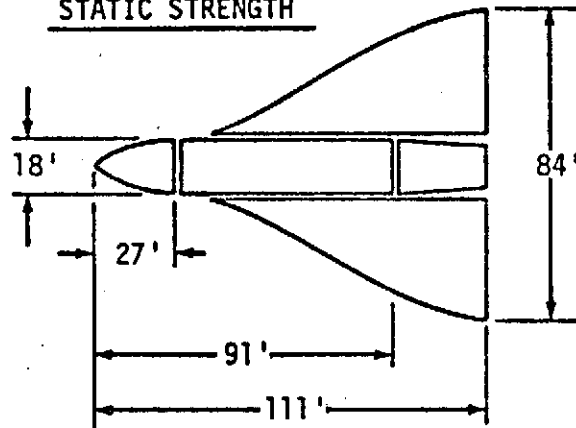
- CREW COMPARTMENT
- FUSELAGE
  - FORWARD
  - MID
  - AFT
- WINGS
- FIN

FATIGUE

62'
40'
18'
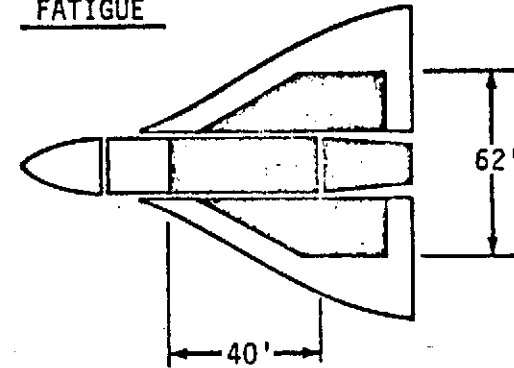
- FUSELAGE
  - MID
  - AFT
- WING BOX
- FIN BOX

☐ PORTIONS OF AIRFRAME USED
IN FATIGUE TEST

● DETERMINATION OF EFFECTS

THERMOMECHANICAL INTERACTIONS EFFECTS WILL BE DETERMINED BY ANALYSES AND DEVELOPMENT TESTING.

● MAJOR STRUCTURAL TESTS

USING THE RESULTS OF DEVELOPMENT TESTS, THE EFFECTS ON A MAJOR TEST ARTICLE CAN BE DUPLICATED BY EITHER REAL TIME OR ACCELERATED TESTING.

● CONCLUSION

PRE-TEST ANALYSES AND DEVELOPMENT TESTING WILL PROVIDE THE NECESSARY UNDERSTANDING OF THERMOMECHANICAL EFFECTS TO SUCCESSFULLY PERFORM CERTIFICATION STRUCTURAL STATIC AND FATIGUE TESTING OF THE ORBITER.

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ORBITER SPECIMEN DAMAGE FROM GVT

- LOW AMPLITUDE INPUT LOADS RESULTING IN LOW INDUCED STRESSES, < 30% OF MATERIAL YIELD STRESS

- WILL HAVE NO EFFECT ON FATIGUE LIFE BECAUSE THE STRESS LEVELS WILL BE BELOW THE ENDURANCE LIMIT ON THE MATERIALS.

- CONDUCTED AT AMBIENT TEMPERATURE; THEREFORE, THERMAL STRESSES WILL NOT AFFECT STRUCTURE.

- CONCLUSION

    THE TEST SPECIMEN WILL BE UNDAMAGED AT THE COMPLETION ON THE GVT AND WILL BE SUITABLE FOR SUBSEQUENT TESTING.

SPECIMEN DAMAGE RESULTING FROM STATIC TESTS

● LIMIT LOAD TESTS

RESEARCH EVIDENCE INDICATES THAT SPECIMEN FAILURES CAN BE EXPECTED
TO OCCUR AT LOADS ≤ LIMIT IN ONE OUT OF EVERY TEN TESTS CONDUCTED.

● LOADS > LIMIT, BUT < ULTIMATE

SPECIMEN FAILURES CAN BE EXPECTED AT LESS THAN ULTIMATE IN
FIVE OUT OF TEN TESTS

● CONCLUSIONS

● PROBABILITY OF FAILURE AT LIMIT LOAD IS LOW.

● PROBABILITY OF FAILURE AT ULTIMATE LOAD IS HIGH. TEST SPECIMEN IS
UNSUITABLE FOR SUBSEQUENT TESTING.

TEST PROGRAM IMPACT OF STATIC TEST FAILURES

CATASTROPHIC FAILURES

● SINGLE SPECIMEN PROGRAM CONCEPT

  A FAILURE WOULD ELIMINATE THE SPECIMEN FOR USE IN SUBSEQUENT TESTING. THEREBY,
  AN ADDITIONAL SPECIMEN WOULD BE REQUIRED TO COMPLETE THE TEST PROGRAM. THIS
  ACTION WOULD NULLIFY THE SINGLE SPECIMEN CONCEPT COST SAVING INTENT AND INDUCE
  PROGRAM SCHEDULING DELAYS.

● CURRENT TWO SPECIMEN PROGRAM PROPOSAL

  WOULD RESULT IN ACQUIRING A NEW SPECIMEN FOR COMPLETING THE STATIC TESTING AND THE
  GVT, WHICH WOULD INCREASE PROGRAM COSTS AND CAUSE SCHEDULING DELAYS.

REPAIRABLE LOCAL FAILURES IN EITHER PROGRAM

● COMPONENT TESTS AND ANALYSES WOULD BE REQUIRED TO DETERMINE THE BEST "FIX" -
  TEST PROGRAM SCHEDULE DELAYS WOULD RESULT.

● TEST CONDUCT TERMINATION TO MAKE REPAIRS - FURTHER PROGRAM SCHEDULE DELAYS ANTICIPATED.

● TEST CONDITIONS COMPLETED PRIOR TO THE FAILURE WOULD BE REPEATED ON COMPONENTS INCORPORATING
  THE "FIX" - ADDITIONAL TESTING EXPENDITURES WOULD RESULT.

STATIC TEST FAILURE SCHEDULE IMPACT
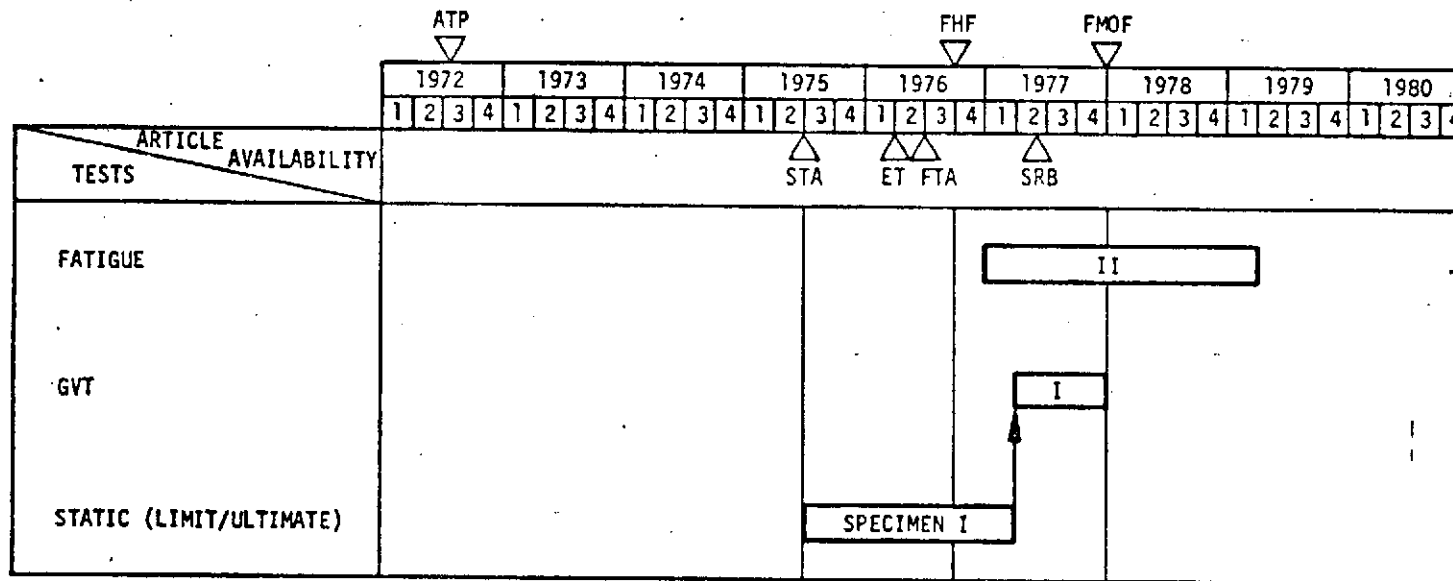
SPECIMEN DAMAGE RESULTING FROM FATIGUE TEST

- TEST LOADING WILL BE < THE DESIGN LIMIT LOADS. GENERAL YIELDING OF THE STRUCTURE WILL NOT OCCUR UNDER LIMIT LOADS.

- THE DESIGN FATIGUE SERVICE LIFE (2,000 MISSIONS) IS LOW WHICH MEANS THE REPEATED LOAD SPECTRUM IS WITHIN THE LOW-CYCLE FATIGUE RANGE (10^5 CYCLES).

- BY DEFINITION LOW-CYCLE FATIGUE DAMAGE RESULTS FROM INELASTIC BEHAVIOR (PLASTICITY AND CREEP). NO GENERAL INELASTIC BEHAVIOR WILL OCCUR DURING THE FATIGUE TEST.

- CONCLUSION

  THE TEST SPECIMEN WILL BE UNDAMAGED AT THE COMPLETION OF THE FATIGUE TEST AND WILL BE SUITABLE FOR SUBSEQUENT TESTING.

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TYPICAL DESIGN STRESS ALLOWABLES

● AL-7075-T73 SHEET t = 0.040 TO 0.249

TEMP. F	MAT'L ALLOW., KSI			DESIGN ALLOW., KSI			$F_{TU}/1.4 < F_{TY}$
	F_{TY}	F_{TU}	F_{CY}	$F_{TY}/1.1$	$F_{TU}/1.4$	$F_{CY}/1.1$	
350	38	40	40	34.5	28.6	36.4	24.7%
80	56	67	55	50.9	47.8	50	14.6%
-100	59	70	58	53.6	50	52.7	15.2%

REF: MIL-HDBK-5 NOV 1967 3.2.7.0 (b)

● Ti-6AL-4V ANNEALED SHEET t ≤ 0.250

350	101	114	110	91.8	81.4	100	19.4%
80	131	139	138	119	99.3	125.4	24.2%
-100	156	164	164	141.8	117.1	149	24.9%

REF: MIL-HDBK-5 NOV 1967 5.4.6.1 (a)

● CONCLUSION:

USING TYPICAL SPACE VEHICLE FACTORS OF SAFETY, THE ALLOWABLE DESIGN STRESSES ASSOCIATED WITH ULTIMATE LOAD ENVIRONMENTS WILL BE APPROXIMATELY 15% LESS THAN THE MATERIAL YIELD STRESS. THEREFORE, NO GROSS YIELDING OF THE STRUCTURE IS EXPECTED UNDER LIMIT LOAD ENVIRONMENTS, ONLY THAT WHICH OCCURS AT STRESS CONCENTRATION POINTS IS EXPECTED.

RATIONALE FOR REVISING CURRENT NR TWO ARTICLE PROGRAM

● CURRENT TWO-TEST ARTICLE PROGRAM

TESTS	ARTICLE AVAILABILITY	1972	1973	1974	1975	1976	1977	1978	1979	1980
					STA	ET FTA	SRB			
FATIGUE							II			
GVT						I — NO SPECIMEN			
STATIC (LIMIT/ULTIMATE)				SPECIMEN I	——— FAILURE 50-50			

ATP ▽   FHF ▽   FMOF ▽
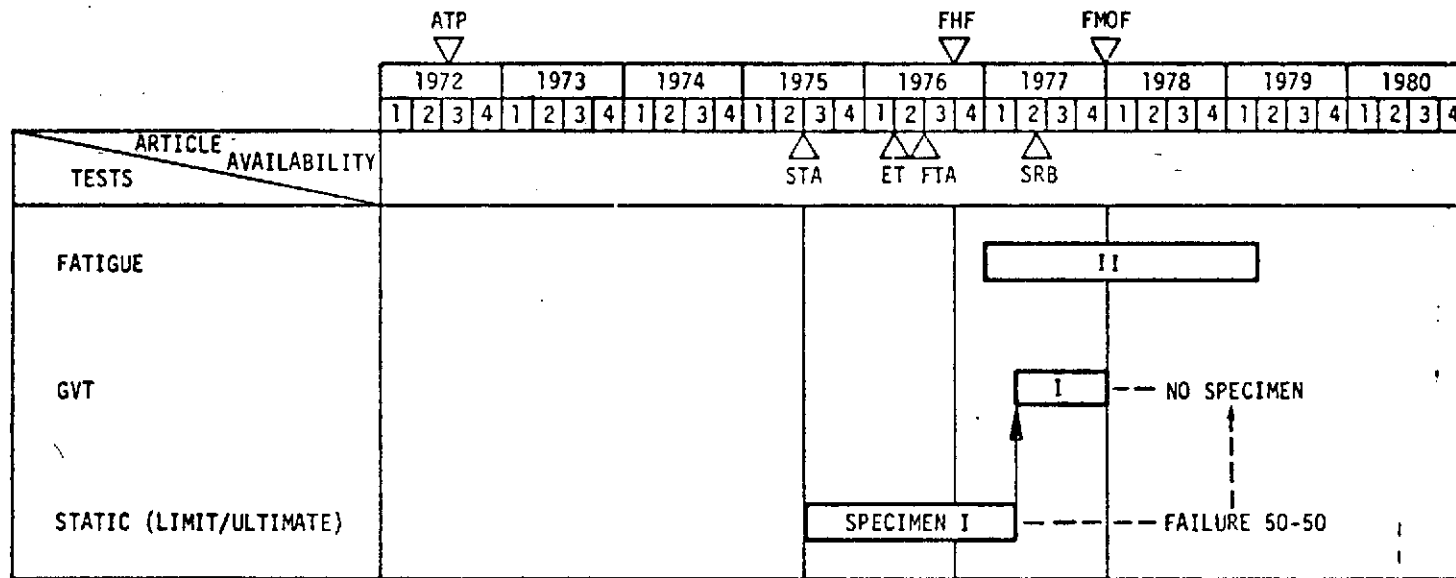
● RATIONALE

THE PROBABILITY THAT SPECIMEN I WILL SURVIVE THE STATIC TEST UNDAMAGED IS APPROXIMATELY 50%; THEREFORE, A PROGRAM POSSESSING LESS RISK IS RECOMMENDED.

● CONCLUSION

REVISE THE CURRENT TWO ARTICLE PROGRAM TO REDUCE THE POSSIBILITY OF SPECIMEN I FAILURE.

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REVISED APPROACH OF TWO TEST ARTICLE PROGRAM

PROGRAM MILESTONE

ATP ▽

CERT. FOR FHF ▽   CERT. FOR FMOF ▽ ◇

	1972				1973				1974				1975				1976				1977				1978				1979				1980		
1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4

TEST ARTICLE AVAILABILITY*

STA △   ET △ △ FTA   △ SRB

CURRENT TWO-TEST ARTICLE PROGRAM	PROPOSED REVISION

ORBITER FATIGUE TEST**   FATIGUE/LIMIT LOAD TEST (REAL TIME THERMAL LOAD)   ▨▨ I ▨▨▨ ▨ II

GROUND VIBRATION TEST   GVT   ▨▨

ORBITER STATIC TEST (LIMIT/ULTIMATE LOADS)   ULTIMATE STATIC LOAD TEST   SPECIMEN I   ▨▨ II ▨▨

OBSERVATIONS:
1. FOUR MONTH SLIDE IN FMOF REQUIRED
2. DELIVERY DATES FOR GVT COMPONENTS NOT MODIFIED

* TEST ARTICLE READY FOR SHIPMENT TO TEST SITE
** ALL TIMES INCLUDE TEST SETUP AND PERFORMANCE

LEGEND:
☐ NR
▨ PROPOSED

POSSIBLE USE OF FLIGHT ARTICLE FOR GVT TWO ARTICLE PROGRAM

PROGRAM MILESTONE

ATP ▽

CERT. FOR FHF ▽

CERT. FOR FMOF ◇ ▽ ◇

	1972			1973				1974				1975				1976				1977				1978				1979				1980		
1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4

TEST ARTICLE AVAILABILITY*,   STA △   ET △ △ FTA   △ SRB

CURRENT TWO-TEST ARTICLE PROGRAM	USE OF FLIGHT VEHICLE AS GVT ARTICLE
ORBITER FATIGUE TEST**	FATIGUE/LIMIT LOAD TEST (REAL TIME THERMAL LOADS) SPECIMEN I II
GROUND VIBRATION TEST	GVT OF FLIGHT ORBITER II
ORBITER STATIC TEST (LIMIT/ULTIMATE LOADS)	ULTIMATE STATIC LOAD TEST SPECIMEN I II

OBSERVATIONS:

1. ONE YEAR SLIDE OF FHF
2. FOUR MONTHS SLIDE OF FMOF

* TEST ARTICLE READY FOR SHIPMENT TO TEST SITE
** ALL TIMES INCLUDE TEST SETUP AND PERFORMANCE

LEGEND:
☐ NR
▨ PROPOSED

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SINGLE ORBITER SPECIMEN TESTING SEQUENCES CONSIDERED

- GVT FOLLOWED BY COMPLETE STATIC AND FATIGUE TESTS

- GVT FOLLOWED BY COMPLETE FATIGUE AND STATIC TESTS

- GVT FOLLOWED BY A COMBINED FATIGUE/STATIC TEST TO COMPLETION

- FATIGUE/LIMIT STATIC, GVT, AND ULTIMATE STATIC

- FATIGUE/LIMIT STATIC, GVT, AND ULTIMATE STATIC (WITH ONE YEAR SCHEDULE SLIDE INCORPORATED FOR FMOF)

● ASSESSMENT

   ● WEIGHT CRITICALITY OF THE SHUTTLE MEANS THAT DESIGN MARGINS OF SAFETY
     → O AND CATASTROPHIC FAILURES OF THE STATIC TEST ARTICLE ARE EXPECTED
     WHEN APPROACHING ULTIMATE LOAD.

   ● SUBSTANTIAL DATA SHOW THAT FATIGUE LIFE IS SIGNIFICANTLY ALTERED BY
     THE APPLICATION OF HIGH STATIC STRESS (e.g. DESIGN ULTIMATE LOADING).
     HIGH PRE-LOAD INDUCE COMPRESSIVE RESIDUAL STRESSES AND LOCALIZED STRAIN
     HARDENING EACH ON WHICH PROLONG FATIGUE LIFE; THEREFORE, THE FATIGUE
     TEST RESULTS COULD BE OBSCURED.

● CONCLUSION: THIS TESTING SEQUENCE IS NOT FEASIBLE

   ● STATIC TEST ARTICLE FAILURE WOULD ELIMINATE THE SPECIMEN FOR USE IN
     SUBSEQUENT TESTS.

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TECHNICAL FEASIBILITY: GVT, FATIGUE, AND STATIC

● ASSESSMENT

    ● PERFORMANCE OF GVT AND FATIGUE TESTS SHOULD NOT PROHIBIT THE
      SUCCESSFUL COMPLETION OF THE STATIC TEST.

    ● CRITICAL FATIGUE DAMAGE WILL BE ACCUMULATED BY LOW-CYCLE FATIGUE
      WHICH OCCURS IN THE PLASTIC RANGE OF THE MATERIAL, BUT STRESSES
      BEYOND THE YIELD STRESS OF THE MATERIAL WILL BE RESTRICTED TO
      ISOLATED LOCATIONS.

● CONCLUSION: THIS TEST SEQUENCE IS TECHNICALLY FEASIBLE

    ● THE SPECIMEN WILL BE UNDAMAGED AT THE COMPLETION OF THE GVT AND
      THE FATIGUE TEST.

TECHNICAL FEASIBILITY: GVT AND COMBINED FATIGUE/STATIC TEST

● **ASSESSMENT**

 - ● THE APPLICATION OF DESIGN LIMIT LOADS CAN BE PROGRAMMED INTO THE FATIGUE TEST LOAD SPECTRUM - HENCE NO INTERRUPTION IN FATIGUE TESTING IS NECESSARY.

 - ● EACH LIMIT DESIGN LOAD IS APPLIED ONCE.

 - ● IF LOCALIZED MATERIAL YIELDING DOES OCCUR, IT WILL OCCUR ONLY ONCE.

 - ● THE INTRODUCTION OF LIMIT LOADS INTO THE FATIGUE LOAD SPECTRUM WILL BE MORE REPRESENTATIVE OF THE EXPECTED SERVICE LOADS.

 - ● THE PROBABILITY OF FAILURE AT LIMIT STATIC LOAD IS LOW.

● **CONCLUSION:** THE TEST SEQUENCE IS TECHNICALLY FEASIBLE

 - ● THE SPECIMEN WILL BE UNDAMAGED AT THE COMPLETION OF THE GVT AND FATIGUE TEST.

TECHNICAL FEASIBILITY: FATIGUE/LIMIT STATIC, GVT, AND ULTIMATE STATIC

● ASSESSMENT

 ● THE APPLICATION OF DESIGN LIMIT LOADS CAN BE PROGRAMMED INTO THE FATIGUE TEST LOAD SPECTRUM - HENCE NO INTERRUPTION IN FATIGUE TESTING IS NECESSARY.

 ● EACH LIMIT DESIGN LOAD IS APPLIED ONCE.

 ● IF LOCALIZED MATERIAL YIELDING DOES OCCUR, IT WILL OCCUR ONLY ONCE.

 ● THE INTRODUCTON OF LIMIT LOADS INTO THE FATIGUE LOAD SPECTRUM WILL BE MORE REPRESENTATIVE OF THE EXPECTED SERVICE LOADS.

 ● THE PROBABILITY OF FAILURE AT LIMIT STATIC LOAD IS LOW.

● CONCLUSION: THIS TEST SEQUENCE IS TECHNICALLY FEASIBLE

 ● THE SPECIMEN WILL BE UNDAMAGED AT THE COMPLETION OF THE FATIGUE, LIMIT STATIC, AND GVT.

SINGLE SPECIMEN SCHEDULES

PROGRAM MILESTONE

ATP

CERT. FOR FHF

CERT. FOR FMOF

	1972	1973	1974	1975	1976	1977	1978	1979	1980
	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4

TEST ARTICLE AVAILABILITY*   STA △ ◇   ET △ △ FTA   △ SRB

CURRENT TWO-TEST ARTICLE PROGRAM   SINGLE SPECIMEN GVT, STATIC, AND FATIGUE

ORBITER FATIGUE TEST**

GROUND VIBRATION TEST   (ONE-YEAR AND NINE-MONTHS EARLY DELIVERY OF SRB)

ORBITER STATIC TEST (LIMIT/ULTIMATE LOADS)

OBSERVATIONS:

1. PROPOSED SCHEDULE WILL NOT SUPPORT FHF OR FMOF
2. EARLY DELIVERY OF SRB'S REQUIRED

LEGEND:
☐ NR
⊏⊐ PROPOSED

* TEST ARTICLE READY FOR SHIPMENT TO TEST SITE
** ALL TIMES INCLUDE TEST SETUP AND PERFORMANCE

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SINGLE SPECIMEN SCHEDULES

| | CERT. FOR FHF | CERT. FOR FMOF |

PROGRAM MILESTONE — ATP

	1972				1973				1974				1975				1976				1977				1978				1979				1980			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4

TEST ARTICLE AVAILABILITY*   STA △◇   ET △ △ FTA   △ SRB

CURRENT TWO-TEST ARTICLE PROGRAM — SINGLE SPECIMEN GVT, FATIGUE, AND STATIC

ORBITER FATIGUE TEST**

GROUND VIBRATION TEST — (ONE-YEAR AND NINE-MONTHS EARLY DELIVERY OF SRB)

ORBITER STATIC TEST (LIMIT/ULTIMATE LOADS)

OBSERVATIONS:

1. PROPOSED SCHEDULE WILL NOT SUPPORT FHF OR FMOF
2. EARLY DELIVERY OF SRB'S REQUIRED

* TEST ARTICLE READY FOR SHIPMENT TO TEST SITE
** ALL TIMES INCLUDE TEST SETUP AND PERFORMANCE

LEGEND:
☐ NR
☐ PROPOSED

SINGLE SPECIMEN SCHEDULES

CERT. FOR FHF
CERT. FOR FMOF
ATP

PROGRAM MILESTONE

1972	1973	1974	1975	1976	1977	1978	1979	1980
1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4

TEST ARTICLE AVAILABILITY* STA △ ◇ ET △ △ FTA △ SRB

CURRENT TWO-TEST ARTICLE PROGRAM	SINGLE SPECIMEN GVT COMBINED FATIGUE/STATIC
ORBITER FATIGUE TEST**	FATIGUE TEST WITH LIMIT STATIC LOADS INCLUDED IN FATIGUE LOAD SPECTRUM
GROUND VIBRATION TEST	(ONE-YEAR AND NINE-MONTHS EARLY DELIVERY OF SRB)
ORBITER STATIC TEST (LIMIT/ULTIMATE LOADS)	

OBSERVATIONS:

1. PORPOSED SCHEDULE WILL NOT SUPPORT FMOF
2. EARLY DELIVERY OF SRB'S REQUIRED

LEGEND:
☐ NR
⊏⊐ PROPOSED

* TEST ARTICLE READY FOR SHIPMENT TO TEST SITE
** ALL TIMES INCLUDE TEST SETUP AND PERFORMANCE

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SINGLE SPECIMEN SCHEDULES

PROGRAM MILESTONE

ATP ▽

CERT. FOR FHF ▽

CERT. FOR FMOF ▽

1972				1973				1974				1975				1976				1977				1978				1979				1980			
1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2		4	1	2	3	4

TEST ARTICLE AVAILABILITY*

STA △   ET △ △ FTA ◇ △ SRB

CURRENT TWO-TEST ARTICLE PROGRAM — SINGLE SPECIMEN FATIGUE/LIMIT STATIC, GVT AND ULTIMATE STATIC

ORBITER FATIGUE TEST** — (ACCELERATED FATIGUE TEST FOR MECHANICAL AND THERMAL LOADS PLUS LIMIT STATIC TEST)

GROUND VIBRATION TEST — (FIVE-MONTHS EARLY DELIVERY OF SRB)

ORBITER STATIC TEST (LIMIT/ULTIMATE LOADS) — ULTIMATE STATIC TEST

OBSERVATIONS:

1. ACCELERATED FATIGUE TEST REQUIRED
2. EARLY DELIVERY OF SRB'S REQUIRED

* TEST ARTICLE READY FOR SHIPMENT TO TEST SITE
** ALL TIMES INCLUDE TEST SETUP AND PERFORMANCE

LEGEND:
☐ NR
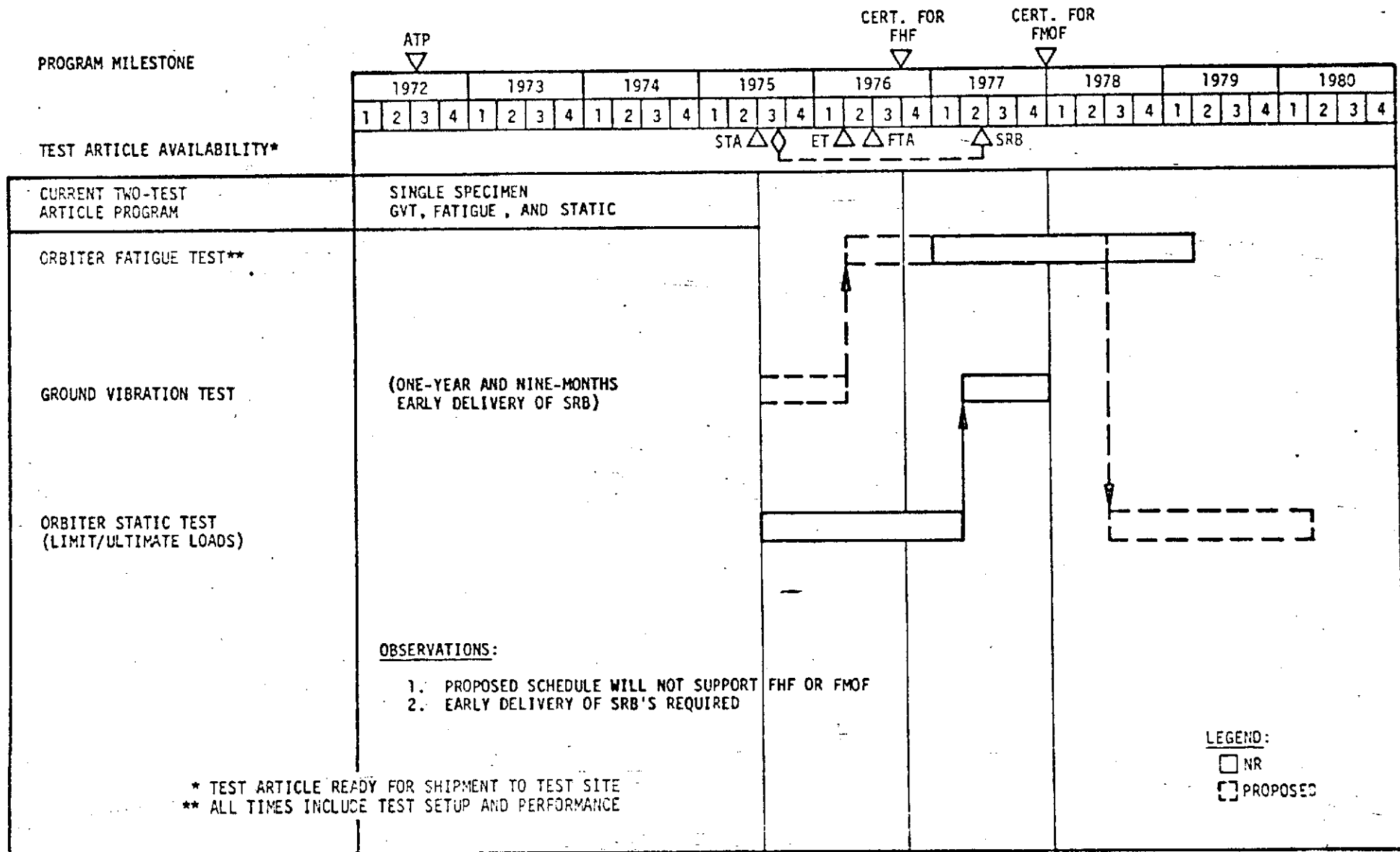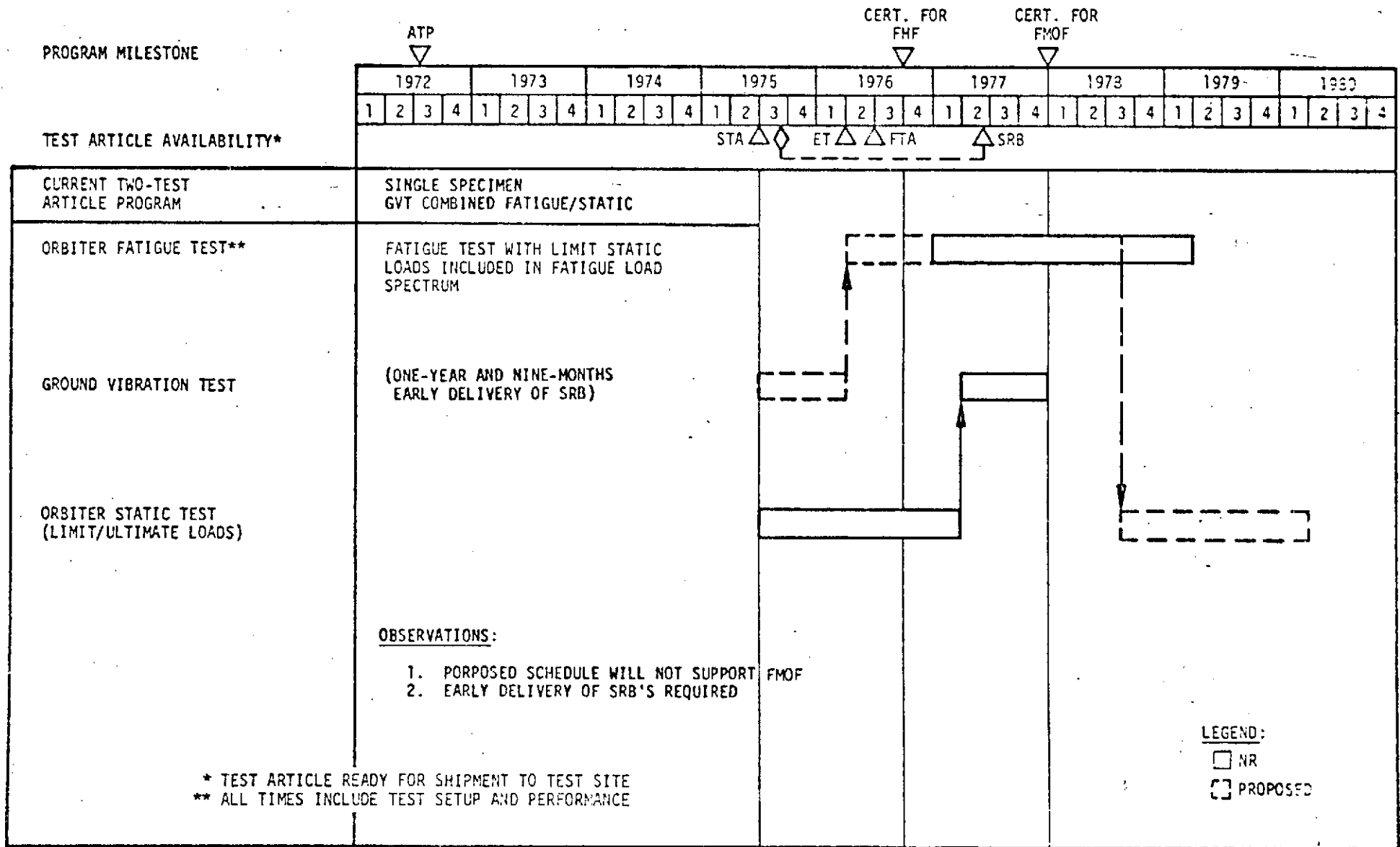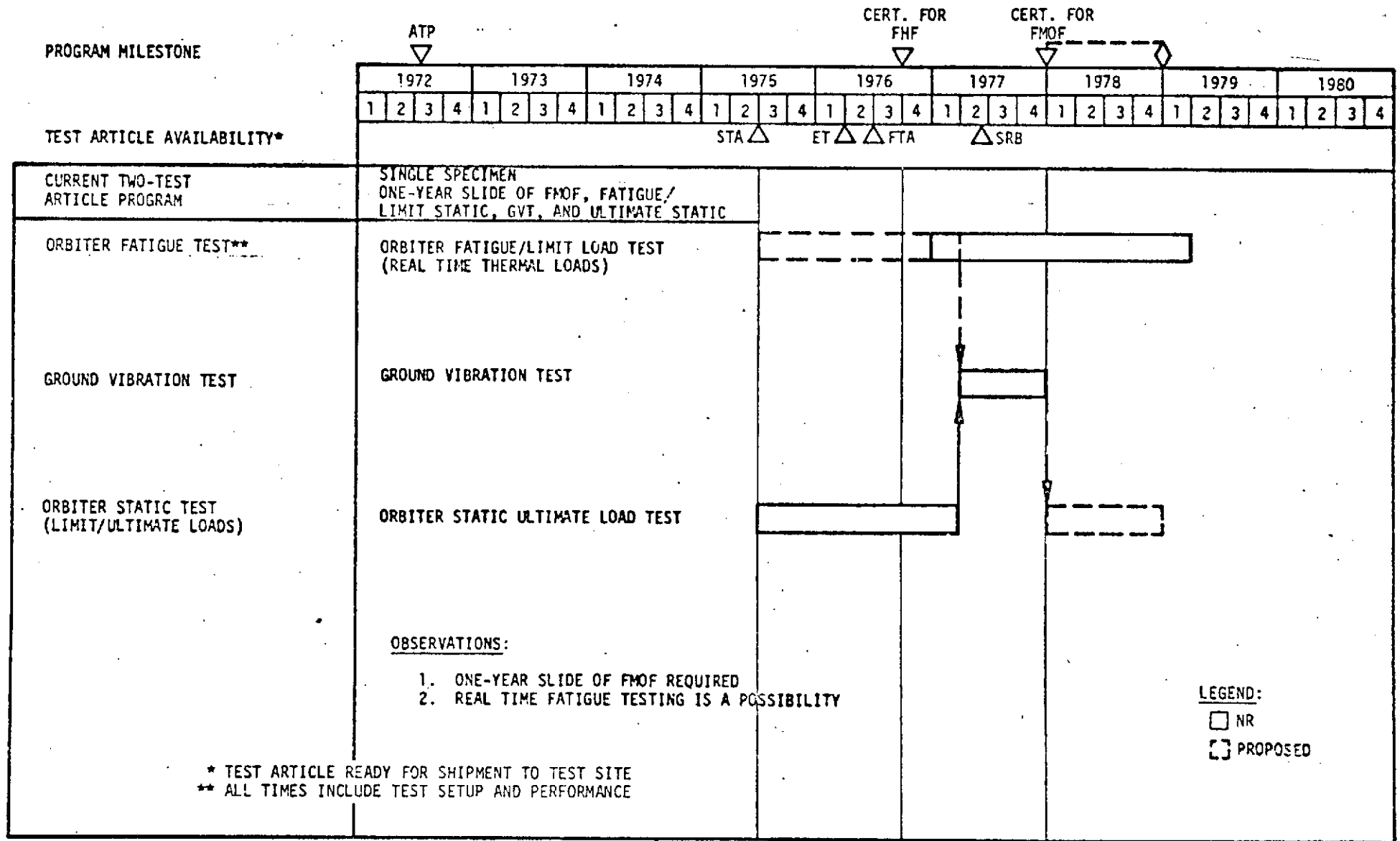☐ PROPOSED

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SINGLE SPECIMEN SCHEDULES

PROGRAM MILESTONE

ATP

CERT. FOR FHF

CERT. FOR FMOF

	1972	1973	1974	1975	1976	1977	1978	1979	1980
	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4

TEST ARTICLE AVAILABILITY*   STA△   ET△ △FTA   △SRB

CURRENT TWO-TEST ARTICLE PROGRAM
SINGLE SPECIMEN
ONE-YEAR SLIDE OF FMOF, FATIGUE/ LIMIT STATIC, GVT, AND ULTIMATE STATIC

ORBITER FATIGUE TEST**
ORBITER FATIGUE/LIMIT LOAD TEST (REAL TIME THERMAL LOADS)

GROUND VIBRATION TEST
GROUND VIBRATION TEST

ORBITER STATIC TEST (LIMIT/ULTIMATE LOADS)
ORBITER STATIC ULTIMATE LOAD TEST

OBSERVATIONS:

1. ONE-YEAR SLIDE OF FMOF REQUIRED
2. REAL TIME FATIGUE TESTING IS A POSSIBILITY

LEGEND:
☐ NR
⊏⊐ PROPOSED

* TEST ARTICLE READY FOR SHIPMENT TO TEST SITE
** ALL TIMES INCLUDE TEST SETUP AND PERFORMANCE

SUMMARY ORBITER TESTING APPROACHES

- **SINGLE ARTICLE APPROACHES:**

	TECHNICAL FEASIBILITY	SCHEDULE IMPACT
• GVT FOLLOWED BY COMPLETE STATIC AND FATIGUE TESTS	NO	YES, UNEXCEPTABLE
• GVT FOLLOWED BY COMPLETE FATIGUE AND STATIC TEST	YES	YES, UNEXCEPTABLE
• GVT FOLLOWED BY A COMBINED FATIGUE/STATIC TEST TO COMPLETION	YES	YES, UNEXCEPTABLE
• ACCELERATED FATIGUE/LIMIT STATIC, GVT, AND ULTIMATE STATIC	YES	YES (5 MO EARLY DELIVERY OF SRB'S)
• REAL TIME FATIGUE/LIMIT STATIC, GVT, AND ULTIMATE STATIC	YES	YES (1 YR SLIDE OF FMOF)

- **REVISION OF CURRENT TWO ARTICLE APPROACH**   YES   YES (4 MO SLIDE OF FMOF)

  - ARTICLE I: REAL TIME FATIGUE/LIMIT STATIC, GVT

  - ARTICLE II: ULTIMATE STATIC

- **USE OF FLIGHT VEHICLE AS GVT ARTICLE**   YES   YES (1 YR SLIDE OF FHF) (4 MO SLIDE OF FMOF)

  - TEST ARTICLE: REAL TIME FATIGUE/LIMIT STATIC, ULTIMATE STATIC

  - FLIGHT VEHICLE: GVT

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TESTING APPROACH CONCLUSIONS

- SINGLE ARTICLE

  - TECHNICALLY FEASIBLE

  - TO ACCOMMODATE WOULD REQUIRE REVISIONS TO CURRENT SCHEDULE

- REVISION OF TWO ARTICLE APPROACH

  - REVISION NECESSARY

  - CURRENT SCHEDULING OF FMOF DELAYED ~ 4 MONTHS

- USE OF FLIGHT VEHICLE AS GVT ARTICLE

  - TECHNICALLY FEASIBLE

  - DELAYS IN CURRENT SCHEDULE WILL OCCUR FOR FHF (1 YR) AND FMOF (4 MO)